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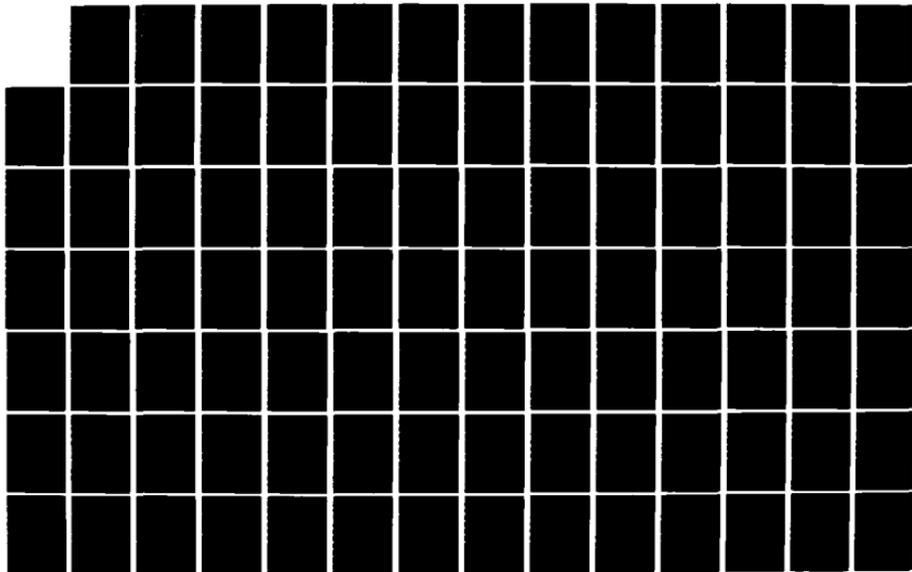
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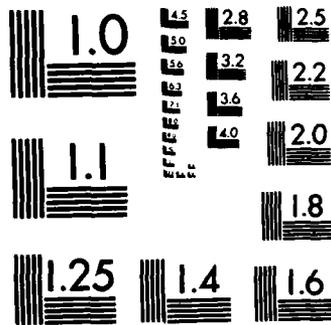
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BRIEF SUMMARY OF THESIS

This study was undertaken to determine if a skeletal anomaly at the junction of the base of the skull and first cervical vertebra affected the development of the facial skeleton. Sixteen dried skulls featuring the anomaly, occipitalization of the atlas, and sixteen normal skulls of comparable size were subjected to radiographic cephalometric analysis. Statistical comparative analysis and correlation analysis were performed on the data. The results indicated the anomalous skulls had retruded and inferiorly directed mandibles, but the maxillas and facial height were unaffected. The observed basilar impression element, related to atlanto-occipital fusion, did not influence facial form.

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THE EFFECTS OF OCCIPITALIZATION  
OF THE ATLAS ON FACIAL SKELETAL  
MORPHOLOGY

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OF THE ATLAS ON FACIAL SKELETAL  
MORPHOLOGY

by

Gaylord D. Noren, B.S., B.S.D., D.D.S.

THESIS

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at

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## INTRODUCTION

Various investigators and researchers occasionally noted that certain people and dried skull material with abnormalities at the base of skull appear to have some alteration in facial form. These facial observations have often been made in a casual descriptive manner, but a distinctive pattern for facial growth in those specimens has not been established. The University of Texas Health Science Center at Houston, Dental Branch, has a collection of dried skulls which bear the anomaly called occipitalization of the atlas. In these skulls the atlas is fused or incorporated into the base of skull in the region of the foramen magnum. Using these skulls and selected normal skulls, an attempt is made to determine if there is a difference in facial form between skulls bearing this cranial base abnormality and the selected normal skulls, if a definite pattern of facial growth occurs in skulls with this anomaly, and whether a cause-and-effect relationship can be established between cranial base development and facial growth.

In this study, a series of measurements and relationships of the cranial base and facial skeleton from right lateral and posterior-anterior cephalometric radiographs of each occipitalized and selected normal skulls is obtained. This collection of data is subjected to statistical analyses comparing the group bearing the cranio-vertebral anomaly with the group of selected normal skulls. Correlation data between measurements within each group are computed to investigate cause-and-effect relationships.

## REVIEW OF THE LITERATURE

The purpose of this literature review is to provide background information concerning occipitalization of the atlas. The definition and description of this anomaly along with its history and controversies, its incidence (how often does it occur) and the embryology of this region with an attempt to assess the etiology of this deformity are salient aspects of this review. In addition, its clinical significance, particularly its neurological effects, its relationships with other abnormalities in the region, specifically basilar invagination, and relationships with facial, head and neck morphology are also very important subjects of this review.

In order to accomplish this task, the review of the literature is divided into six sections, although there may be some overlap and duplication in some areas. The six sections are as follows:

1. Anatomical Analysis
2. Incidence of Occipitalization of the Atlas
3. Embryology of the Atlanto-Occipital Complex
4. Neurological Considerations
5. Basilar Impression, Invagination and Platybasia
6. Craniofacial and Other Skeletal Relationships

In the section dealing with basilar invagination, a discussion of certain measurements pertaining to the basiocciput and the controversy surrounding them is included.

### Anatomical Analysis

Lawrence (1827) presented a specimen possessing fusion of the first, second and third cervical vertebrae, fusion of the atlas with occiput, displacement of the atlas anteriorly in an oblique fashion as related to the foramen magnum, destruction of the left half of the atlantal ring, and projection of the posterior part of the atlantal ring and odontoid process of the axis into the foramen magnum and the cavity of the skull respectively. These alterations, thought to be caused by a large fluid-filled tumor of the spinal canal in the neck with direct communication with the brain, produced tortuosity of the spinal canal and contraction of the canal to one-third of its usual size.

Hussey (1857) examined a dried specimen in which the first cervical vertebra was intimately and almost completely united to the occipital bone along the entire margin of the foramen magnum. In addition, the second, third, and fourth cervical vertebrae were completely welded together, converting the spinal canal into an almost complete bony cylinder.

Turner (1867) described an interesting pathological specimen exhibiting firm ankylosis of the occipital condyles to the articular surfaces of the atlas and ankylosis of the axis with the atlas. Both sites of fusion were accompanied with posterior displacement and rotation of the atlas and axis. The odontoid process of the axis was separated from its articulating facet on the anterior atlantal ring. Collectively, these abnormal relationships produced great diminution in size of the canal in this locality. A little behind each occipital condyle a bar of bone united the posterior ring of the atlas with the margin of the foramen magnum. Sufficient space existed between the bar and the condyle to permit the transmission of the vertebral artery and

suboccipital nerve. A similar bar of bone existed between the atlas and axis which also allowed passage of the second cervical nerve.

Allen (1880), in his classification of the variations of the atlas, noted that two variations frequently accompany atlanto-occipital fusion:

(1) Deficient development of the posterior arch of the atlas, usually seen as a gap between the lateral halves of the arch; and (2) Articulation, followed by fusion, between a strong process ascending from the atlantal transverse process and the processus jugularis of the occipital bone.

Macalister (1893) in his treatise concerning the development and ossification of the atlas, discusses the various ways in which assimilation of atlas to the base of the skull can occur:

- A. Congenital fusion of the foetal cartilage of the atlas to that of the occipital region. This condition is excessively rare. The specimen of this condition was the subject of a meningocele.
- B. The whole ring of the atlas may become inseparably united to the edge of the foramen magnum.
- C. The articular process and posterior arch, or part of it, may be fused with the contiguous parts of the occiput, while the central part of the anterior arch is separated from the basi-occipital by a small interspace.
- D. The articular processes may be ankylosed to the occipital condyles, while the arches and transverse processes are free. This, the commonest condition, is an acquired pathological condition due to osteitic or arthritic inflammation.
- E. Another method whereby fixity of the atlas to the skull may be produced is by the attachment of the transverse process to the jugular process of the occipital bone. These cases are due to ossification in the ligamentous apparatus between the transverse process and the jugular process, and are extensions outwards of the gleno-transverse bridge, with which they may be continuous. This method of fusion can occur in one of three ways:
  1. By the meeting of a down-growing paroccipital process of the skull with an up-growing spur from the atlas.
  2. The processus paroccipitalis may be a down-growing column from the occiput, starting close to the outer edge of the exoccipital next to the occipito-mastoid suture, touching the upper

surface of the transverse process of the atlas, which is not raised to meet it, either articulating with it by a flat surface or ankylosed to it.

3. The up-growth of a styliform process in the form of a pillar-like elongation from the posterior superior angle of the transverse process of the atlas articulates or ankyloses with a normal paroccipital process.

Slade (1895) presents a thorough review of the literature concerning atlanto-occipital fusion providing case reports and observations of such notable investigators as Allen, Luschka, Boxhammer, Schniffer, Kussmaul, Lawrence, Macalister, Grawitz, Langerhaus, Sommer and Dwight.

Dorsey (1897) reports of a dried specimen with an unusual occipito-atlantal articulation without ankylosis. The right jugular process of the occipital bone extends downwards and slightly backwards into a prolongation measuring 23 mm. in length and 17 mm. in greatest diameter. On the anterior surface of this process, toward its lower extremity, is a nearly circular articular facet which measures 10 mm. in diameter. On the atlas there is a corresponding facet on the posterior border of the right transverse process. While the slight backward tendency of the elongated jugular process is enough to avoid fusion with the atlas, it is not sufficient to permit the atlas from assuming an abnormal position. As a result, the atlas makes an angle of about 20 degrees to the sagittal plane of the foramen magnum. Other abnormal characteristics of the atlas include a bifid left transverse process, bilateral large well-defined supernumerary foramina posterior to the vertebral foramen (that which conveys the vertebral artery) and a partial bridging, almost complete, of the groove for the vertebral artery by a spiculum of bone arising near the middle of the posterior arch.

Dwight (1904) offers a partial classification of the conditions that lead to a false position of the head and a loss of motion of the head and neck, based on specimens of his own observation. The variations are arranged in the following classes:

CLASS I. Diminution of the number of cervical vertebrae.

CLASS II. Fusion of cervical vertebrae. The most common site is fusion of the axis with the third vertebra.

CLASS III. Union of the atlas and occiput.

Section A. By fusion.

- Group 1. The atlas is perfectly formed, the articular processes are well-developed, and the posterior arch stands widely separated from the base of the skull. The atlas is fused with the occiput at the joints and possibly at the anterior arch. The atlas is also placed in almost perfect symmetry. "It has been suggested that the condition follows an arthritis due to a sudden exposure to cold. It may be objected that in that case the process would hardly affect both joints so evenly, and that if it affected one it is not that the other would degenerate to the same extent. While I am inclined to think the conditions congenital, I admit that it is far from certain."
- Group 2. The fusion involves one-half of the posterior arch, which is but slightly developed and incorporated (or assimilated) with the border of the foramen magnum. There is always a median deficiency at the posterior arch; the articular processes are always fused; the lateral mass of the atlas is more prominent on the free side; and the corresponding end of the transverse process is both higher and further advanced (rotated forward) than the other. The amount of fusion of the anterior arch varies, but there is almost always a chink between some part of it and the occiput. "As to the etiology of this condition there is great uncertainty, but there is every reason to believe that as a rule it is congenital. Schiffner asserts that it is the result of a chronic disturbance of nutrition during development which causes an arrest of the growth of the atlas." Dwight considers this group the more common variant which is in disagreement with Macalister who holds the Group 1 variety more common.

Section B. By a paramastoid process.

It was pointed out in the cases of asymmetrical fusion of half the atlas with the edge of the foramen magnum that the transverse process of the side of the atlas which is free is further forward in relation to the base of the skull. Here the same thing occurs on the side of the paramastoid process.

Smith (1908) is in agreement with the Russian anatomist Swjetschnikow in his classification of fusion of the atlas to the occiput, which is divided into three categories:

(1) Those acquired as the result of tuberculosis, syphilis, arthritis deformans, arthritis adhesiva chronica, etc; (2) those acquired in the fetus in utero, as the result of pressure in an abnormal pelvis; (3) purely congenital cases, in which, during the process of growth, the sclerotomes, which are developing into the cranium, become abnormally attached to the sclerotome of the first cervical segment.

In regards to the second category, which some writers deny its existence, Smith comments:

Whether or not this pressure is brought about in the way described, there can be no doubt that simple fusion (and sometimes also partial assimilation of the atlas) occurs in a number of cases in conjunction with a distinct pushing inward of the parts of the occipital bone around, and especially in front of, the foramen magnum, leading to a condition of basikypnosis.

Smith asserts:

True assimilation of the atlas is rarely, if ever, an isolated anomaly of the cranio-vertebral axis. It is often associated with profound disturbances of other regions of the vertebral column and malformations of the cranium.

Once again Smith refers to the works of Swjetschnikow in describing one characteristic of assimilation of the atlas:

The sulcus arteriae vertebralis becomes converted into a canal when the atlas fuses with the occipital bone, and where assimilation takes place, the opening of this canal becomes displaced forward, until it is brought quite close to the foramen hypoglossi.

Smith presents a case in which this process has gone one stage further. "The channel for the suboccipital nerve has actually become confluent with the hypoglossal canal."

Smith alludes to the controversy between assimilation of the atlas and manifestation of an occipital vertebra. "No case of assimilation of the atlas is ever so complete as to be indistinguishable from an extreme case of manifestation of an occipital vertebra, and vice versa." However, should such an indistinguishable event occur, "the only possible evidence of absolutely decisive value would then be the knowledge of the existence or absence of a separate atlas."

Smith states Swjetschnikow's criteria for the diagnosis of manifestation of an occipital vertebra in difficult cases:

The absence of the opening between the anterior arch of the atlas and the basi-occipital (his "spatium atlanto-occipital anterius"), which is constantly present in assimilation of the atlas, the absence of foramina transversaria and sulcus arteriae vertebralis.

Dwight (1909) publishes a case report of a cadaver specimen exhibiting both assimilation of the atlas and an occipital vertebra. In addition, the specimen possesses fusion of the second and third cervical vertebrae, a supernumerary thoracic or lumbar vertebra, fusion of the bodies of the sixth and seventh cervical and first thoracic vertebrae through prominent exostoses, a supra-sternal bone fused with the manubrium, and perhaps a hypochordal brace, a superfluous ossicle locked between the odontoid process of the axis and the anterior arch of the atlas. He states that this case adds further credence to the remark by Smith that "true assimilation of the atlas is rarely, if ever, an isolated anomaly of the cranio-vertebral axis."

Dwight becomes critical of those investigators who argue about certain "manifestations" on the bases of isolated skulls as belonging to one region or to the other:

We must recognize that the case is the same as at other transitional parts of the spinal column. A twenty-fifth vertebra may be a sacral vertebra or a lumbar vertebra, or a cross between the two. Similar observations may be made at the two ends of the thorax. It is idle to

discuss which vertebra a particular vertebra is. All we can say is which one it is like. It would seem that in discussing the occipital region we are slow to apply the principles we follow elsewhere.

Gladstone and Erichsen-Powell (1915) formulate criteria to distinguish between manifestation of occipital vertebra and fusion of the atlas with the occipital bone:

Manifestation of Occipital Vertebra

Condyles oval in outline; convex; converge anteriorly; surfaces directed downwards and laterally; slight constriction separating anterior from posterior part of condyle. The condyles encroach only slightly, or not at all, on the foramen magnum.

The anterior arch usually has no facet for the "dens epistropheus." In rare cases, however, a third occipital condyle may be developed on an "arcus praebasioccipitalis." The anterior arch is usually completely fused with the occipital bone.

Posterior arch not so wide as that of the atlas, and less distinctly marked off from the occipital bone. Usually no gap between it and the occipital. No canal for vertebral artery and suboccipital nerve between the posterior arch and the occipital bone. A groove is sometimes present on the under surface

Fusion of Atlas with Occipital

Inferior articular facets nearly circular in outline; slightly concave; directed downwards and medially. The lateral masses encroach considerably on the foramen magnum. Cases, however, in which the atlas has fused with the occipital bone sometimes show rounding off of the inferior articular facets, so that they may resemble the condyles of the occipital bone. This is due to the movements of flexion and extension of the head being transferred from the occipito-atlantal articulation to the joints between the atlas and axis.

The anterior arch usually has a facet for the odontoid process of the axis (dens epistropheus). There is usually an anterior tubercle for the attachment of the M. longus capitis. The anterior arch is frequently separated by a gap from the anterior margin of the foramen magnum.

Posterior arch wider, forming an arc of a circle, the centre of which would be near the pharyngeal tubercle. The posterior arch is separated from the occipital bone by a canal for the vertebral artery and suboccipital nerve, or there is a distinct gap between the

of the bone for the vertebral artery, immediately behind the condyles.

Transverse process as a rule presents no foramen for the vertebral artery, and is less separated from the occipital bone.

posterior arch and the occipital bone, with a groove on the former, as in the normal bone.

Transverse process frequently free, and pierced by canal for vertebral artery. Costal element may, however, be rudimentary, in which case a groove for the artery may usually be recognized in front of the true transverse process; it may be united or articulate with the occipital bone by means of a paroccipital process.

Harrower (1923), in his literature review, points out conflicting views concerning the distinction between manifestation of an occipital vertebra and assimilation of the atlas in the more complicated cases:

Kollman considers that the shape and curvature of the articular surfaces on the skull base are the essential aids, while Swjetschnikow asserts that the absence of the sulcus for the vertebral artery and the foramen in the transverse process with absence of the anterior atlanto-occipital interval are indications of manifestation of an occipital vertebra.

In regards to Kollman's criterion, Harrower describes three specimens with unquestionable assimilation of the atlas in which the inferior articular surfaces of the fused atlas approximate the form of occipital condyles, particularly on the side where the assimilation is more complete. "It is fairly obvious that one cannot dogmatise on the shape and curvature of the condyles."

We are therefore justified in concluding that the shape and curvature of the condyles is primarily determined by functional factors, to admit of flexion and extension of the skull. Flexion and extension, as is well known, occur in the other moveable regions of the spine by compression and relaxation of the intervertebral disc which is absent between the atlas and the occiput and therefore the articular surfaces are modified to compensate for this factor. We might expect that if the atlanto-occipital articulation is ankylosed the succeeding articulation would become modified, given sufficient time, to permit of the required movement.

In assessing Swjetschnikow's formula, Harrower presents two cases, which are similar to one presented by G. Elliot Smith, that represent an advanced stage of assimilation:

In having neither anterior atlanto-occipital interval, foramen in the transverse process, nor sulcus for the vertebral artery, it should be diagnosed as an occipital vertebra; yet this assumption is negated by the very presence of the third or median condyle in its particular form, and by the presence of the canal for the suboccipital nerve running into the hypoglossal canal.

Green (1930) presents an unusual case of unilateral atlanto-occipital fusion, of which the opposite side is missing, but must be considered as normal. The unusual features are the encroachment by the free medial extremity of the incomplete posterior arch into the foramen magnum, produced by the medial end jutting abruptly for about one centimeter into the foramen magnum, and the separation of the medial end of the anterior arch from its fellow from the opposite side, leaving a smooth surface which was covered recently by cartilage.

Nayak (1931) describes a case of atlanto-occipital union and fusion of the axis with the third cervical vertebra in which only a line of fusion on the internal aspect of the anterior arch remains of the atlanto-occipital interval, and modifications of the inferior articular surfaces of the atlas (convex and oval in shape) serve as an adaptation to provide slight nodding movements of the head.

Bezi (1931) asserts:

As the atlas may be more or less melted together with the os occipitale after various inflammatory processes, the term "assimilation" should be reserved for congenital cases, i.e., those based on malformation. The adhesions of the bones arising in extra-uterine life (in most cases with inflammatory origin) should be called "synostosis."

Bezi also points out:

A synostosis may interfere with a cisternal puncture. This is very unlikely in the case of assimilation of the atlas, because under such

circumstances there is, as a rule, an absence of the posterior arch of the atlas, thus facilitating puncture. Consequently, if by roentgenogram and puncture, an occlusion of the posterior space is detected, the condition is, most probably, a synostosis, therefore an acquired condition and not an assimilation.

Rau and Sivasubrahmaniam (1933) relate a case possessing some features indicative of manifestation of an occipital vertebra as well as assimilation of the atlas on one side and of simple fusion on the other. On the assimilated side, there is a foramen behind the dorsal bar of the transverse process which gives the appearance of duplication of the foramen transversarium. They suggest that the vertebral artery enters the skull directly through this foramen without passing through the foramen magnum.

Motwani (1936) describes two cases of atlanto-occipital fusion. In one case, the atlas appears to be twisted about its vertical axis so that the anterior tubercle is in line with the pterygoid hamulus on the right side, and the jugular process of the occipital bone and the right superior articular facet of the atlas are partially fused. In the other case, there is no obvious foramen transversarium in the transverse process of the fused atlas, which is fused to the jugular process of the occipital bone, producing a foramen between the condyle and the jugular process for the passage of the vertebral artery.

Lanier (1939) re-emphasizes the classical differentiating characteristics between assimilation of the atlas and manifestation of an occipital vertebra advocated by Swjetschnikow (1906) and Bystrow (1931).

Among the characteristics of atlas assimilation are: (1) a foramen or canal between the anterior arch and the occipital, called the atlanto-occipital space; (2) frequent development of paramastoid processes; (3) presence of a canal for the vertebral artery and the first cervical nerve located between the posterior arch of the atlas and the base of the occipital bone; (4) retention of the normal shape and inclination of the inferior articular facets of the atlas.

Lanier presents an unusual specimen in which all four criteria indicate "assimilation" on the right side and all four points satisfy the diagnosis of "manifestation" on the left side. The epistropheus (axis) is markedly asymmetrical, thought to be produced by the fusion of the blastemal body from an occipital vertebra on the right side. There is the presence of a separate ossicle which, when articulated with the left inferior facet on the base of the occipital bone, lies "in the same plane with that part of the element fused with the occipital whose right lateral mass, anterior arch, and posterior arch are in agreement with criteria for an assimilated atlas." This separate ossicle which possesses superior and inferior articular facets, a transverse process with a foramen, a rudimentary posterior arch, and a transverse groove suggesting the groove for the vertebral artery tends to complete a "normal" atlas.

Peyton and Peterson (1942) propose their criteria to distinguish assimilation of the atlas from manifestation of an occipital condyle (vertebra), also called proatlas:

1. The joint surfaces on the proatlas, like those of the normal condyles of the occipital bone, are so placed that if the planes of these surfaces are projected they converge caudalward, while the joint surfaces of the assimilated atlas are placed like the normal inferior articular surface of the atlas and, if projected, converge cranialward. This is the most constant and reliable differential feature.
2. In assimilation of the atlas there is almost always a foramen on each side between the posterior arch of the fused atlas and the occipital bone, for passage of the vertebral artery and first cervical nerve in their normal relationship to the atlas and base of the occipital bone.
3. Other differences are more or less inconstant and unreliable. Frequent development of a paramastoid process and the presence of a canal between the anterior arch and occipital bone in atlas assimilation are given by Lanier as differential features. According to Bystrow (1931) a complete posterior arch has never been observed in "manifestation of an occipital condyle." Of all

the elements of a proatlas, he finds the most frequent manifestation to be the formation of some part of an anterior arch (67 per cent).

Peyton and Peterson also add:

In roentgen examination it is often difficult to determine the presence of synostosis between the atlas and occipital bone unless body section roentgenography is used. The deformity of the assimilated atlas, however, is visible and the latter is reported as rudimentary, hypoplastic, or deformed.

With reference to the different characteristics between occipital vertebra and atlanto-occipital fusion, Hadley (1948) writes:

Of differentiating value is the shape of the condyles. On the occipital vertebra these are oval and convex and in the anteroposterior view their articular surfaces face laterally in a caudal direction. The condyles on the undersurface of an assimilated atlas, however, are flattened (rarely slightly convex) and their surfaces visualized in the anteroposterior view are directed medially in a caudal direction.

Flexion-extension studies will reveal a fixation of movement between atlas and occiput. The transverse processes bear foramina for the vertebral arteries. There is a space between the dorsal arch of the atlas and the occiput for passage of the suboccipital nerve and the vertebral artery. There is an articulation on the anterior arch for the odontoid. As with the occipital vertebra, the accessory eminences on one or both sides may encroach upon and distort the foramen magnum. The anterior arch or the posterior arch may not be completely fused with the occiput. Non-segmentation may have occurred only on one side.

McRae and Barnum (1953) write:

In the anatomical literature several criteria have been advanced to allow differentiation of occipitalization of the atlas from manifestation of an occipital vertebra when only the dried skull is available for examination. At various times the various criteria have been proved not valid in all cases. Even if the complete spine is available it may not help. Probably criteria based on the position of the hypoglossal and suboccipital nerves and vertebral artery are most reliable but even these have been questioned.

McRae (1953) also asserts:

Much of the confusion regarding occipitalization of the atlas and manifestation of an occipital vertebra is unnecessary. If the criteria found in dried skulls are considered less absolute, if the cervical vertebrae are carefully inspected, and if the hypoglossal nerves and vertebral artery can be seen, one will seldom make the diagnosis of an occipital vertebra.

Concerning the radiographic interpretation of occipito-vertebral deformities in the living individual, McRae (1953) states:

The essential point in the diagnosis of occipitalization of the atlas is some degree of bony union between the skull and the atlas. The parts of the atlas that must be clearly visualized are the anterior and posterior arches, the superior facets, and the transverse processes.

McRae and Barnum (1953) state that "lack of movement between the skull and atlas is not an absolute criterion" for atlanto-occipital fusion. They further offer some observations and comments concerning 25 cases of living patients diagnosed as possessing occipitalization of the atlas based on radiographic studies and clinical evaluation, some of which were confirmed later at operations and/or at autopsy:

In all of our cases of assimilation there seemed to be bony continuity between the anterior arch of the atlas and the anterior lip of the foramen magnum. In most cases the cortex of the anterior arch was continuous with that of the basi-occiput and in some the medulla of the basi-occiput was continuous with that of the anterior arch. In these there was no anterior atlanto-occipital interval.

The bony masses representing the fused occipital condyles and lateral masses of the atlas were often asymmetrical. Usually the high facet had a horizontal or nearly horizontal articular surface, while the low facet had an oblique surface as seen in the open-mouth view, the lateral edge being lower than the medial edge. Sometimes their asymmetry seemed due to the occipital condyles, or lateral masses, being of different size; other cases were due to different degrees of assimilation of the right and left sides of the atlas; and others were due to combinations of these two factors. In no case did the joint between the assimilated atlas and axis resemble an atlanto-occipital joint.

The transverse processes of the atlas might be normal, but this was rare. Even when free from the occipital, the transverse process would often have either the costal element or lateral half missing so that a complete arterial foramen was not present. Even when fused to the occipital (most often at the tip of the transverse process), the transverse process might look almost normal. In 5 cases a distinct paramastoid process was present, not attached to the atlas, and there was no transverse process on the atlas.

Some trace of the posterior arch of the atlas was present in all but 2 cases. Usually it was a bony fringe on the posterior edge of the foramen magnum which was directed downward and inward producing more or less constriction of the spinal canal. This fringe became smaller

as it passed laterally and forward around the margins of the foramen magnum and often disappeared completely before the lateral mass was reached. It might persist as a rolled edge for the lateral margin of the foramen magnum.

Spillane, Pallis and Jones (1957) point out "the terms 'occipitalization' and 'assimilation' of the atlas are either used synonymously, or to describe varying degrees of atlanto-occipital synostosis." "The term 'assimilation' of the atlas is perhaps justifiable when all components of the vertebra are in bony continuity with the base of the skull." In clinical situations, "such complete synostosis can only be diagnosed after antero-posterior and lateral tomograms of the foramen magnum have been taken."

Occipitalization of the posterior arch of the atlas can usually be diagnosed from a good lateral film, taken with the neck in full flexion, a procedure which, in normal persons, will produce maximum separation of the posterior arch from the overlying part of the squamous occiput. The anterior arch may sometimes be considered occipitalized on the plain lateral film, but the lateral tomogram may show that it is not in fact fused to the clivus. Plain films taken through the open mouth and centred on the odontoid may suggest the presence of synostosis at the atlanto-occipital articulations, but antero-posterior tomograms are required for confirmation of such fusion and in order to establish a diagnosis of occipitalization of the lateral masses.

Spillane et al. also note in their report of 24 neurologically disabled patients with bony and/or neural anomalies of a developmental nature in the region of the foramen magnum:

Occipitalization of the atlas was frequently associated with other anomalies of the cranio-vertebral junction. The association with fusion of cervical vertebrae was particularly frequent, 6 of our 7 patients with occipitalization showing fusions at various levels of the cervical spine. Five patients had basilar impressions but only 2 had chronic atlanto-axial dislocation. This is of interest in view of the statement made by McRae and Barnum (1953) that when assimilation of the atlas is associated with neurological signs "the most significant finding... (is) an odontoid process of abnormal size, or in an abnormal position, or with an abnormal mobility." Atlanto-axial dislocation was found in two-thirds of their cases of occipitalization with neurological complications.

Lombardi (1961) offers his experience with manifestation of the occipital vertebra. He reports that, according to Kollman (1905), the phenomenon, called "manifestation of the occipital vertebra," is caused by the "failure of the distal occipitoblast to fuse with the others (producing) abnormal bone formations on the external surface of the skull around the occipital foramen." This anomaly may occur alone or in combination with other local malformations, though rarely develops neurologic signs and symptoms.

The most common of these malformations is the third condyle, followed in descending order of frequency by the paracondyloid process, isolated ossification between the atlas and the occipital bone, basilar processes, fissures of the basi-occiput, and a bony mass fused with the occipital foramen. The last mentioned variant appears to be the most dangerous form because it may lead to direct compression of the spinal cord.

Most of the time manifestations of the occipital vertebra have no clinical significance. There are rare exceptions: the third condyle, when well-developed, may limit the mobility of the head; the paracondyloid process, fusing with the transverse process of the atlas, may force the head into a continuous attitude of flexion (*caput obstipum*); and, most importantly, the abnormal osseous formations which originate from the arches or from the transverse apophyses of the pro-atlas, when fused with the base, will narrow the occipital foramen and may provoke neurologic symptomatology of a compressive type.

Epstein (1962) remarks about various anomalies of the cervico-occipital junction:

The proatlas, or occipital vertebra, also may take the form of a partially separated entity, consisting of more than one bit of bone, and may distort the foramen magnum by rendering it irregularly narrow because of the appearance of accessory eminences along its periphery.

Referring to atlanto-occipital fusion, Epstein states:

In the event of complete fusion, no symptoms appear. However, partial fusion may be associated with instability of the atlas and axis, abnormal mobility of the odontoid being produced by lack of fixation of the ligaments, particularly the transverse ligament.... Atlanto-occipital fusion may be accompanied by fusion of two or more cervical segments. Accessory eminences occur on one or both sides of the foramen magnum, narrowing and distorting this area, much the same as occipital vertebrae.

Deformity of the margins of the foramen magnum and the base of the skull frequently accompanies bony abnormalities of the craniovertebral junction. The foramen magnum becomes misshapen and encroached upon because of assimilation of the atlas or the presence of transitional vertebrae. Because of this, the tip of the dens projects into the cervical spinal canal just below and at the foramen magnum, thereby narrowing the space available for the medulla oblongata and the proximal cervical spinal cord.

Bharucha and Dastur (1964) report on 40 patients with craniovertebral anomalies of which 23 patients possessed occipitalization of the atlas.

All grades of assimilation of the atlas were seen, from total assimilation where no part of the atlas was visible, to partial, where there was fusion of only one lateral mass. Fusion of C<sub>2</sub> and C<sub>3</sub> vertebrae was a common additional finding and was present in 14 cases.

They further remark:

The occipitalized atlas, with fused C<sub>2</sub> and C<sub>3</sub> vertebrae and a posteriorly displaced odontoid, forms a distinct radiological group. Here, as the result of atlanto-occipital fusion, the nodding movement of the head is relegated to the atlanto-axial joint, thereby imposing an additional strain on the ligaments of the medial and two lateral joints. The ensuing laxity of ligaments is responsible for backward odontoid displacement and spinal compression.... It was worth noting that in 2 cases of occipitalization the compression occurred at a lower level, at fused C<sub>2</sub> - C<sub>3</sub> vertebrae in one and between C<sub>2</sub> and C<sub>5</sub> due to Albers-Schönberg's disease (diagnosed from myelographic studies).

Of the clinical features associated with occipitalization of the atlas, Bharucha and Dastur point out that a short neck and low hair line, usually related to Klippel-Feil syndrome, were observed most frequently, being present in 19 of their 23 patients; and of these 19 patients, 16 had restricted neck movements.

McRae (1969), in his experience dealing with occipitalization of the atlas, notes that approximately one-third of his patients had congenital fusion of C<sub>2</sub> and C<sub>3</sub>. Flexion and extension at the atlanto-occipital joint is abolished when only one side of the atlas is fused to the occiput. The other side may remain free or may be fused to the axis.

He also relates the following information concerning the odontoid process in patients with occipitalization of the atlas:

In occipitalization of the atlas, the odontoid process is often high in position, lying within the effective foramen magnum and competing with the medulla oblongata for space.... When these patients flex and extend the head, the odontoid process moves backward and forward, a type of atlanto-occipital dislocation. Because the facets of C<sub>1</sub> and C<sub>2</sub> have flat surfaces, unlike the normal curved facets of the occipital bone and the atlas, this backward and forward movement is, however, rocking rather than a rotatory movement.

Reflecting on radiographic interpretation of occipitalization of the atlas, McRae (1971) makes some observations:

Lack of movement between skull and atlas on roentgenographic examination is not the only criterion. Sometimes the skull does not move on the atlas when marked basilar impression, or soft-tissue ankylosis of the skull and the atlas, is present.... On lateral roentgenograms and tomograms the cortex of the anterior arch of the atlas is seen to be continuous with the basi-occiput. In still other cases the medullary cavity of the anterior arch of the atlas appears to be continuous with the medullary cavity of the basi-occiput.... Seldom is a facet for the odontoid process obvious on the posterior surface of the fused anterior arch.

McRae also comments on the perennial controversy concerning manifestation of an occipital vertebra:

The various criteria are not valid in all cases, however. Even the presence of the cervical spine may not help. Before the diagnosis of manifestation of an occipital vertebra is made, it is generally agreed that one must show that there is no foramen for the vertebral artery or greater occipital nerve between the abnormal ossicle and the occiput. Criteria based on the position of the hypoglossal and suboccipital nerves and the vertebral artery are probably the most reliable.... One criterion of a normal atlas is that the atlas should not be fused to the skull at any point. Then, and only then, can an unusual bony formation around the foramen magnum be deleted from the group of occipitalized atlases and placed in the group of occipital vertebrae.

Incidence of Occipitalization of the Atlas

The incidence of occurrence of the various cranio-vertebral anomalies has been recorded in the literature during the last 125 years. Considerable variation exists among the works of different observers. Occipitalization of the atlas seems to occur with the frequency of 1 in every 50 skulls examined to 1 in approximately 500 skulls, depending on the investigator.

Hussey (1857) relates that Mr. Alexandre, a dealer in skeletons, had observed more or less complete bony union between the occiput and the first cervical vertebra in 1 out of every 200 skeletons he had prepared for sale (0.5%).

Macalister (1893) states that in the Cambridge collection, the occurrence of atlanto-occipital ankylosis was 0.14%. He also reports on the findings of other investigators:

- Lombroso recorded such fusion in 0.84% of the skulls in the Beinhaus at the battlefield of Solferino;

- Legge found 5 cases out of 780 in a graveyard at the city of Camerino (0.64%);

- Lombroso also observed atlanto-occipital fusion in 4 out of 51 criminal skulls (7.8%);

- De Paoli noted this condition in 2 out of 4 criminal skulls (50%).

Slade (1895) remarks that in his examination of the skull collection in the Peabody Museum in Cambridge, only six were discovered among the entire number where synostosis was present even to the smallest degree.

Slade also quotes a portion of a paper prepared by Sommer from which the following remarks are taken in regards to his findings at the Allenberg Lunatic Asylum:

In 100 lunatic skulls only two cases of synostosis! But, surely, still it cannot be said that two percent is a correct ratio of its frequency among lunatics. I give this number with all reservations, and simply remark that in 50 skulls that I have since carefully examined, I have found no cases.

Harrower (1923) describes 9 cases of variations in the cranio-vertebral region collected from 800 cases belonging to the Anatomical Department of Glasgow University (1.1%). Six of the specimens undoubtedly exhibited assimilation of the atlas (0.75%), while the remaining three controversial cases showed marked divergence from the normal condition of the cranial base (0.38%).

Montiero and Tavares (1928) report on the frequency of occipitalization of the atlas among the Portugese. They found 7 cases of occipitalization in 358 specimens in the Museum of the Institute of Anatomy in Oporto (1.95%). After this study was completed, the museum skull collection received 19 skulls and 2 occipital bones of which two specimens with this anomaly were observed (9.5%). Together these two groups yielded 9 out of 379 skulls with occipitalization of the atlas (2.37%). However, in a review of skull material at the Institute of Anthropology at the University of Oporto, none of the 171 specimens examined presented with this form of synostosis (0.0%). Cumulative data among these studies yield 9 atlantally fused skulls out of 550 (1.64%).

Montiero and Tavares also relate some significant observations from other investigators:

- Sueiro found 2 skulls with occipitalization of the atlas in 100 specimens at the Museum of the Institute of Anatomy at Lisbon (2%). He also observed only one skull with atlantal occipitalization out of a total of 1176 skulls belonging to the Ferraz collection of Macedo (Musée Bocage of the Faculty of Science) (0.085%). In another series only one atlantally fused skull was found in 133 unidentified skulls (0.75%). The summation of his

study from three different collections in Lisbon yielded 4 cases of occipitalization of the atlas in 1409 skulls examined (0.28%).

- Maximino Correia performed two studies in Coimbra. From 1433 skulls in the collection of the Institute of Anthropology of the University of Coimbra, 6 specimens possessing this variation were noted (0.42%). In another study 2 cases of the atlas fused to the occipital bone were observed in 47 skulls and isolated occipital bones in the museum of the same university (4.26%). Collectively, these two studies yielded 8 skulls bearing atlanto-occipital fusion out of 1480 (0.54%).

Montiero and Tavares point out that there is a tendency, in relatively restricted collections, to selectively retain those anatomical specimens which bear anomalous structures. This observation accounts for the exceedingly high incidence of atlanto-occipital fusion in the three medical facilities in Oporto, Lisbon and Coimbra, yielding percentages of 1.95%, 2.0% and 4.26% respectively. In the large studies by both Sueiro and Correia, more realistic indicators of incidence are provided, 0.28% and 0.54% respectively.

Bystrow (1931) observed 33 cases of occipitalization of the atlas in 1570 skulls yielding a percentage of 2.10%. He also reiterated the results of other investigators:

- Friedlowsky found 4 skulls out of 2000 bearing assimilation of the atlas (0.2%).

- Russell observed 4 cases with this anomaly from a collection of 1055 skulls (0.38%).

- Batujew, in a skull collection at the Anatomical Institute of Odessa University, found occipitalization of the atlas in 1.2% of their specimens.

- Marselli noted 1.5% of his series of skulls, numbering less than 700, possessed synostoses of the atlas.

Lanier (1939) relates his observations of incidences of cervico-occipital anomalies at the Washington University (St. Louis). He observed 13 skulls out of 1246 exhibiting two or more characteristics of manifestation of an occipital vertebra (1.04%). Assimilation of the atlas was noted in only 2 skulls (0.16%).

List (1941) cites the findings of other investigators concerning the frequency of fusion of the atlas with the occipital bone. Besides those studies previously mentioned, the observations of Tramontano-Guerritore and Odnoralow are reviewed:

- Tramontano-Guerritore found 41 cases of atlanto-occipital fusion among 1475 adult skulls (2.78%).

- Odnoralow observed 8 assimilations of the atlas in approximately 1500 skulls (0.53%).

Lombardi (1961), using precise lateral roentgenograms, laminagraphy (including the transverse axial plane), and other projections, examined 4000 consecutive patients. From this series of patients, he was able to identify 19 cases of manifestation of an occipital vertebra (0.47%). He cites Saucer who observed only 5 cases among 1119 skulls in an ossuary (0.45%).

McRae (1971) wrote that occipitalization of the atlas is present in about 0.75% of the general population (however, he does not cite the source of this information). In only one-fourth to one-third of this number does it cause neurologic symptoms and signs.

Srisopark (1974) evaluated 692 skulls belonging to the skull collection at the University of Texas Dental Branch at Houston. Of these skulls, only 6 exhibited fusion of the atlas to the occipital bone (0.87%).

### Embryology of the Atlanto-Occipital Complex

Multiple theories and opinions have been advanced concerning the growth and development of the cervical spine, the atlas and axis in particular, and its relationships with the developing occipital bone. In this section, attempts are made to express certain popular views of atlanto-occipital development, and to relate the etiology of cranio-vertebral anomalies to developmental incongruities. Atlanto-occipital fusion from acquired causes will also be mentioned.

In a study of the developing fetus, infants and young children, Macalister (1893) comments on ossification of the atlas and relates his findings to observations made by other prominent investigators.

- Bichat describes five centers of development--one for the anterior arch, two for the posterior arch, and two for the lateral masses.

- Cloquet remarks that more frequently there are three or four centers--one or two for the anterior arch and two for the rest of the bone.

- Mechel describes the anterior arch as arising by one or several nuclei, these uniting together before they join the lateral masses. A rounded posterior ossicle also is found in the middle of the posterior arch.

- Humphry describes the anterior arch as sometimes formed by an ingrowth from the lateral masses, with no independent center.

- Gray speaks of the anterior arch as usually completed by ingrowth from the lateral centers, which he calls neural processes. Occasionally a separate nucleus exists which joins the neural processes in front of the pedicles, or there may be two that join into one.

From his study of the development of the atlas, Macalister makes the following deductions:

1. Ossification begins early in the seventh week (in utero) by two centres, one at the root of each hinder arch, and spreads rapidly backwards into the arch, more slowly forwards into the articular mass, and outwards into the transverse processes.
2. About the middle of the first year, ossification begins ectos-  
teally in the anterior arch; most commonly by two unequal but  
closely-approximated centres, which speedily unite, sometimes  
within a few months of their appearance.
3. The posterior arch closes late in the fourth year. (He found no  
evidence of a median nucleus in twenty cases.)
4. The anterior arch synostoses to the lateral mass late in the fifth  
year.
5. The limbs of the arterial foramen are variable in their dates of  
closure. The hinder and outer boundaries and the outer edge of  
the anterior boundary are ossified from the transverse process;  
only the anterior and inner part is costal. Closure usually takes  
place in the sixth year.

In regard to synostosis, Slade (1895) writes that this condition, according to several authorities, is due to arthritic affections, commencing at an early period, but rarely diagnosed during life. He refers to Dwight's opinion that "in some cases, especially where the arches are separate, the joints become ankylosed through disease."

In many of the striking cases, in which the arch seems little more than a ridge on the occiput, we must look for the cause in some early disturbance in the development of the spine, such as causes the suppression of a vertebra or occasionally of half a vertebra, or the increase or diminution in the number of ribs.

As to the theory, which was originally advanced by Rust and since maintained by Italian observers, that synostosis may be traceable to the practice of carrying heavy burdens upon the head, it should be said that, while this may not be impossible, especially as the greater frequency of this abnormality is stated to be found among the Italian than among other Continental nations....a much larger number of well-established facts must be brought together before synostosis can be proved to become hereditary.... The same may be said in regards to traumatic causes, such as heavy blows upon the back of the neck, either criminal or accidental, as by snow-slides from houses, injury to spinal column by falls upon stairs and sidewalks, to children by falls from bed during sleep, by strains however produced; all of these may cause inflammation that extending upwards, terminates in an ankylosis between the atlas and the base of the skull, to be verified only after death.

Bardeen (1908) gives his views on the development of the cervico-occipital region:

During the earlier stages of development the cervical vertebrae resemble those of the thoracic region. The two regions soon become differentiated from one another by the much greater development of the costal processes of the thoracic region.

In the cervical, as in the thoracic vertebrae, the development of a region of loose tissue in the base of the primitive ventral process serves to separate the costal element from the transverse process. In this loose tissue an anastomosing artery extends from the intersegmental artery on the posterior to that on the anterior side. The anastomosing artery between the costal element and transverse process of the seventh cervical vertebra remains small, but more anterior anastomosing arteries give rise to a large continuous vessel, the vertebral artery, which extends anteriorly between the costal processes and transverse processes of the root of the vertebral artery.

Commenting on chondrification of cervical vertebrae, Bardeen writes:

In the more proximal cervical vertebrae, the centers of chondrification appear as basal plates lateral to the anterior end of the bodies of the vertebrae. With these they soon fuse. From the plate-like base, chondrification extends rapidly into the main part of the arch. From the neural arches, laminar, articular and transverse processes are developed. The costal elements have separate centers of chondrification which soon fuse proximally with the bodies of the vertebrae and distally with the tips of the transverse processes of the vertebrae.

Bardeen states that the presence of vertebral arch elements is manifested in the upper cervical region in higher mammals and Man. In the membranous stage, bands of tissue which connect the bases of the neural processes differentiate from the ventral margins of the primitive discs. Froriep called these elements hypochordal braces. In Man, a hypochordal brace becomes well developed in the formation of the atlas.

Regarding the unique formation of the epistropheus (axis), the atlas and the basioccipital bone, Bardeen makes the following remarks:

1. The epistropheus differs from the other cervical vertebrae by its union with the body of the first cervical vertebra. This union takes place through the transformation of the intervertebral disc into cartilage.

2. The base of each hemi-arch of the atlas becomes temporarily fused with its body, but this fusion is incomplete and soon is followed by the development of dense fibrous tissue between the arch and the body. At the same time the hypochordal brace becomes cartilaginous and unites the arches of the atlas in front of the body.
3. The articulation between the lateral mass of the atlas and the superior articular surfaces of the epistropheus, also true of the atlanto-occipital diathrosis, seems to be formed in the inter-ventral membranes rather than in the interdorsal membrane as in other intervertebral diathroses.
4. For a brief period of time, the bases of the neural arches of the atlas and epistropheus, together with the tissue intervening between the bases of arches of the atlas and the occipital, become fused into a nearly continuous mass of pre-cartilage.
5. Opposite the last occipital myotome, the axial mesenchyme is differentiated, like that of the spinal sclerotomes, into a light anterior half and a dense posterior half, or sclerotome. In the spinal region each sclerotome joins with the light half of the sclerotome next posterior in giving rise to the body and arch processes of a spinal vertebra. Contrary to this, the occipital sclerotome becomes associated with the lighter tissue of its own segment and with the tissue into which this is continued anteriorly.
6. From the tissue derived from the first and second sclerotomes, and not utilized in the formation of the atlas and epistropheus, are derived the various ligaments which unite these bones.

Smith (1908) comments on the progressive and regressive theory of the spinal column:

In the transition from fish-like vertebrata to the amniota, several vertebrae become fused and assimilated to the occipital bone. Most recent writers regard cases of congenital fusion and assimilation of the atlas as a further stage of the evolutionary process; in other words, as an addition of yet another vertebra to those already absorbed into the constitution of the amniote cranium; and such anatomists look upon these anomalies as "progressive" modifications of the vertebral column.

On the other hand, when "the structure of the vertebra becomes unveiled," as occurs with manifestation of an occipital vertebra, "this is looked upon as a 'regressive' modification."

Smith reflects on Dwight's opinion of this matter:

"Variations which separately seem either reversive or progressive generally lose that appearance when the whole spine is considered; moreover, after the occurrence of the original error in development (for example, the fusion of the first cervical somite to the occipital mass), there is a tendency for the spine to assume, as nearly as possible, its normal disposition and proportions." In other words, there is an attempt on the part of Nature to correct the original error by compensatory modifications of the other parts of the spinal column.

Gladstone and Erichsen-Powell (1915) comment on the embryology of occipital bone:

The composite nature of the occipital bone is indicated by a study of the hypoglossal nerve, and the cranio-vertebral skeleton of the lower vertebrates.... The hypoglossal nerve is generally believed to represent one or more of the anterior spinal nerves, and its transformation into a cerebral nerve can be traced in passing through the vertebrate series.

Froriep believes that the occipital region in the human subject is formed by the fusion of four rudimentary vertebrae, corresponding to three primary roots of the hypoglossal nerve. Of these four, only the posterior is at all independent; its development in the early stages resembles that of the vertebrae and loses its identity only when fused with the parts in front of it.

Commenting on the development of the axis, Gladstone and Erichsen-Powell make the following assertions:

1. The height of the dens and body taken together is greater than the bodies of two cervical vertebrae and an intervertebral fibrocartilage. It is in fact nearly equal in height to the bodies of three cervical vertebrae.
2. The dens is formed from two centra, in addition to the centrum of the epistropheus: a lower, the body of the atlas; an upper, the body of a pro-atlas or last occipital vertebra.
3. The main portion of the dens, including a part of the apex, is ossified from the two primary ossific centres.
4. The extreme tip of the odontoid process is ossified by a separate centre, which appears about the third year.

They further comment on the variations observed in the cranio-vertebral complex: "The appearance of an additional vertebra in front of the atlas was formerly regarded as an addition to the total number of elements in

the vertebral column." This additional element was called the "pro-atlas." The occasional occurrence of such a vertebra in individuals was regarded as indicating a general tendency towards lengthening of the vertebral column.

However, this tendency, if present, should not be regarded as a lengthening due to the addition of a new vertebral element, but rather as taking place at the expense of the cranium, by liberation of an occipital vertebra.

Gladstone and Erichsen-Powell state that arrest of development is thought to account for some cases of manifestation of an occipital vertebra, due to the lack of normal fusion of the last occipital vertebra with the rest of the occipital bone. Manifestation of an occipital vertebra is sometimes associated with the development of additional tendons of insertion for the longissimus cervicis and splenius cervicis muscles.

In case of fusion of the atlas with the occipital bone, it is certainly true that the separation of the atlas from the occipital bone by the formation of arthro-dial joints is secondary; and that the cartilage of the atlas and occipital bone are primarily united by a continuous tissue, characterised by its staining properties, and the large number of closely set nuclei. In cases of fusion of the atlas, this tissue does not break down to form a diarthrodial joint; in this sense, there is an arrest of the normal development of the arthro-dial joints between the atlas and condyles of the occipital bone.

They also mention that increased intra-uterine pressure may account for fusion of atlas with the occipital bone in some cases, particularly when the region around the foramen magnum is pressed into the posterior cranial fossa.

Gladstone and Erichsen-Powell acknowledge these findings:

A few cases of fusion of the atlas with the occipital bone are undoubtedly due to disease occurring either in utero or after birth. They usually can be distinguished by signs of inflammation, which affect not only the bones immediately concerned but also neighboring parts.

Harrower (1923) comments on intra-uterine pressure as a cause for assimilation of the atlas:

In the more complete forms of assimilation, the elements must be fused at a very early stage of development. It is now well known that the ovum becomes embedded in the uterine mucosa, and it is extremely doubtful whether pressure could produce an alteration at this stage (Schiffner's Drücktheorie). It seems more probable that it is a fault in the arrangement of the parts which leads to so many abnormalities in other tissues.

With regard to the lesser forms of fusion of the atlas, it is conceivable that abnormal intrauterine pressure may produce the condition under consideration. Yet, again, pressure in a fluid is essentially equally distributed; and therefore, the abnormality could only be produced if there was a deficiency of liquor amnii or if the amniotic cavity were divided into loculi by abnormal adhesions.... It is reasonable to suppose that any pressure which was great enough to induce fusion of the neck vertebrae would be sufficiently great to produce evident deformities of other parts and probably also of the brain capsule. This also points to the cause of assimilation being intrinsic, not extrinsic.

Oetteking (1923) reviewed the popular theories involving the development of the skull. The vertebral theory of the cranium, proposed by Goethe and Oken and later modified by Aeby, postulated the cranium is derived from cranial vertebrae. From a posterior to anterior orientation, these vertebrae are called vertebrae occipitalis, temporalis (consisting of basi-sphenoid with alae magnae and the ossa parietalia), frontalis (consisting of the pre-sphenoid with the alae parvae and the ossa frontalia), and nasalis (comprised of the ethmoid, nasal bones and vomer), which was added by Aeby. Against the vertebral theory, Thomas Huxley argued that the cranial bones originate and differentiate in an unsegmented skull, based on the results of a wide comparative study. At the time of Oetteking's paper, Huxley's views appeared to have been accepted by the majority of scientists.

Oetteking also related the concept of "metamery of the cranial axis" as fostered by Gegenbaur:

While agreeing with Huxley on the autonomous anlage of the bones of the brain case, and the unsegmented state of the ethmoid and partly the orbital region, he conceived the greater posterior portion of the skull base derived from the coalescence of vertebrae or vertebral anlagen. This theory of hypothetical cranial vertebrae appeared to be

justified on the basis and in view of the previously existing visceral arches and the cervical nerves pertaining to them, as well as of the extension of the chorda dorsalis into the cartilages later constituting the cranial axis.

Oetteking referred to the works of Froriep in which the anlage of three to four occipital vertebrae was evident in early ontogenetic stages.

Their development, however, remained rudimentary with the exception of the most caudal one, which attained more advanced stages before its definite merging with the other rudiments into the cranial axis. It received the designation by Froriep of the "Occipitalwirbel."

Oetteking described Stöhr's theory of "caudal progression of the cranium" as support for occipital metamery:

The n. hypoglossus and its affinity to the n. vagus group on the one hand and the first cervical nerves on the other, together with the assumed successive assimilation of cervical vertebrae, gave rise to Stöhr's theory of "caudal progression of the cranium." According to this theory, the homologa of the nn. hypoglossus and accessorius Willisii are not to be seen in the cerebral nerves of lower vertebrates, but in their first spinal nerves. Involved in this supposition is the gradual assimilation of vertebral elements into the skull.

Bezi (1931) reported on the acquired form of atlanto-occipital fusion:

According to newer knowledge this synostosis may be congenital or acquired--the latter being usually the result of inflammatory processes. In such instances certain deformations occur on the vertebrae, that is, exostoses, irregular thickenings or bony ridges.

Bezi discussed the pathogenesis of inflammatory ankylosis as found in an acute purulent arthritis, progressing into chronic arthritis deformans:

There is frequently a pathologic involvement of the cartilage of the joint in cases of purulent arthritis, viz., a necrosis of the cells, preceded by fatty degeneration and splitting of the matrix into fibers. After the immigration of leukocytes, the cartilage becomes liquid or separated from the bone. There develops a sequestering or rarefying osteitis in the denuded bone resulting, when completely healed, in ankylosis. If the cartilage does not degenerate, as occurs in a milder case after the inflammatory process has subsided, the capsule of the joint shrivels up, and the result is limited motion (pseudo-ankylosis). The purulent inflammation may become chronic. At such times, the inflammation stops on the development of a bone-forming osteitis fibrosa on the denuded joint surfaces. Thus the denuded joint surfaces grow together (true ankylosis).

Lanier (1939), in a descriptive article of a skeletal specimen exhibiting features of manifestation of an occipital vertebra on one side and assimilation of the atlas on the other, discussed some observations, theories, and opinions concerning the formation of the cranio-cervical junction:

The phenomenon known as "manifestation of an occipital vertebra" is attributed to incomplete incorporation of the last occipital sclerotome into the base of the occipital region.

The comparative anatomical studies of Lachi and Chiarugi and the embryological investigations of Terry and Weiss have shown that the bodies of the atlas and of the occipital vertebra are similarly separated from the rest of their elements. The epistropheus takes up the normal mode of development for the vertebral series, but has added to it the blastemal body of the atlas which Froriep and Macalister found to produce the odontoid process and the anterior articular process of the epistropheus.

According to Haffner, these variations (anomalies of the cranio-vertebral region) would have been established before the end of the fourth week of development.... The blastemal halves of vertebral anlagen are independent in segmentation and differentiation through the fourth week.

Lanier mentioned the genetic concept proposed by Kühne in 1936:

Kühne, who has established the inheritance of either cranial or caudal shifts at the cervico-thoracic, thoraco-lumbar, lumbo-sacral, and sacro-coccygeal borders, states that manifestation of an occipital vertebra is a cranial shift, and that assimilation of the atlas is a caudal shift at the occipito-cervical junction, but that he is inclined to suspect no correlation between occipito-cervical shifts and shifts at other vertebral borders.

In his study of 13 skulls having characteristics of manifestation of an occipital vertebra and 2 skulls exhibiting features of assimilation of the atlas, including their respective vertebral columns, Lanier concluded:

Variation at the cranio-vertebral border in a small series seems unassociated with variations at the lower intersegmental vertebral borders and, therefore, is unassociated with hereditary control of the latter as established by Kühne.

List (1941) briefly reviewed the embryonic development of the occipital bone, atlas, and axis:

The posterior part of the skull (occipital bone) is formed by the fusion of primarily metameric bone segments, that is, by coalescence of three or four occipital sclerotomes, which correspond to the three primary roots of the hypoglossal nerve. The most caudal of these sclerotomes, the so-called proatlas, retains a certain independence, but loses its identity later, when it becomes united with the proximal parts. Failure of fusion of this last occipital sclerotome with the remaining occipital segments has been termed "manifestation of the occipital vertebra" (Kollman, Gladstone and Erichsen-Powell).

The atlas is formed by three elements, viz., the caudal half of the last hypoglossal (occipital) sclerotome and the cranial and caudal semisegments of the first cervical sclerotome. The body of the atlas is lost early; it furnishes the main mass for the odontoid process. The anterior arch of the atlas, a remainder of the hypochordal arch, usually contains one median center of ossification; in other instances there are two symmetric areas of ossification, or rarely there is none. The lateral masses and the transverse processes are formed by a large center of ossification on each side. The median cleft in the posterior arch resulting from this development is normally closed at the end of the first decade of life. Nonfusion of the posterior arch (spina bifida posterior) is of rather common occurrence. Occasionally the seemingly absent posterior arch of the atlas may be fused with that of the axis.

The axis is a complex structure which develops from three primitive vertebrae. The second cervical sclerotome furnishes the main mass, consisting of a center of ossification for the body and two others for the transverse processes and posterior arch. The dens is formed by two centers of ossification. The major distal portion represents the original body of the atlas, whereas the tip, the "ossiculum terminale," is derived from the body of the proatlas (last occipital vertebra).

List further commented on the genesis of atlanto-occipital fusion and anomalous development of the axis:

There are several possible causes responsible for bony union of the atlas with the occiput: In a small group of cases fusion is the result of a pathologic process (such as arthritis or tuberculosis) occurring in fetal or in early post-natal life.... The condition in such cases may be designated as (pathologic) synostosis of the atlas with the occiput. Some authors expressed the belief that intra-uterine trauma, viz., pressure on the hyperextended fetal head, is an important factor in the development of the deformity. In a majority of cases, however, the condition undoubtedly occurs on a purely developmental basis and represents a variation in the craniovertebral boundary. One may refer to this type as assimilation of the atlas to the occiput.

Anomalous development of the axis appears to be less common than that of the atlas; however, cases of spina bifida of its posterior arch,

bifid dens and partial fusion with the posterior arch of the atlas or of the third cervical vertebra have been described. Fusion of the second and third cervical vertebral bodies and of other cervical vertebrae is not rare.

Hadley (1948) discussed the embryology of the spine and occiput with emphasis toward causation of occipito-vertebral anomalies:

Three phases in the development of the spine are recognized: (1) blastemal or membranous; (2) chondrogenous; (3) the bony stage. Segmented groups of cells form about the notochord very early; lighter staining cells in front and darker ones in the caudal part of each segment or sclerotome. In the chondrogenous stage the cephalic (lighter staining) half of one sclerotome unites with the caudal half of the segment ahead to form a vertebra. The atlas, however, includes three half segments, i. e., all of the first cervical sclerotome and the cephalic half of the second cervical.

In the early stage there is no division between the spine and the skull. The sclerotomes or somites which later form the vertebrae are continuous in front with three or four postotic segments, the hypoglossal or occipital. In the chondrogenous stage these segments form the occipital plates and later fuse to form the continuous occipito-sphenoid cartilage. Within this develop the four or five centers of the occipital bone which surround the foramen magnum.

If the posterior-most hypoglossal sclerotome is incompletely assimilated with the others forming the base of the skull, an occipital vertebra results. This is said to be a normal condition in certain mammals of the weasel tribe such as the wolverine. If segmentation is not completed between the occiput and atlas, a so-called atlanto-occipital fusion results.

These errors of segmentation may result from diminished vitality of the germinal cells, thus interfering with the hereditary or growth power of the fetus. Schiffner, in speaking of this unstable condition of nonsegmentation of the atlas, asserts that it is the result of a chronic disturbance of nutrition during development, which causes an arrest of the growth of the atlas.

At about the age of four or six years a separate ossicle forms about that portion of the notochord residuum, within the terminal ligament, just cephalic to the odontoid. This normally becomes united to form the tip of the odontoid about six years later. According to some authorities, it corresponds to the body of the last (hypoglossal) segment. If such union does not take place, this element may remain as a separate bony structure, the so-called ossiculum terminale, lying within and deforming the foramen magnum.

Hadley related that "rarely fusion of the atlanto-occipital joints may result from disease: arthritis, osteomyelitis, echinococcosis, syphilis, tuberculosis and actinomycosis."

McRae and Barnum (1953) provided an excellent overview of the embryology of the occipital-vertebral junction, supporting the statements made by the previously cited investigators. In addition, they made the following comments of interest:

The spinal nerves are situated in relation to the anterior clear halves of the sclerotomes.... Since the atlas forms from the anterior clear halves of the first and second spinal sclerotomes and the posterior dense half of the first spinal sclerotome, there are two spinal nerves, C<sub>1</sub> and C<sub>2</sub>, associated with it, one nerve above and one below.

In the case of occipitalization of the atlas (assimilation of the atlas into the occipital bone) one must assume that the hypochordal arch of the atlas with its attached neural arches is continuous with the basal plate (occipital sclerotomes). The centrum of the atlas fuses with the centrum of the axis, and the centrum of the atlas separates itself from the hypochordal arch by the transformation of incompletely differentiated cartilage into blastemal tissue (in normal development). The fact that approximately 50 per cent of cases of assimilation of the atlas have an associated fusion of the second and third cervical vertebrae (both bodies and arches) may signify the absence of ingrowth of the myocoele (v. Ebner) into the third or axial somite and might be evidence in favor of diffusion of a chemical organizer, or else the lack of organizer in the whole area.

Sensenig (1957), having at his disposal through the Department of Embryology of the Carnegie Institution of Washington much more extensive material than was available to previous investigators, undertook an intensive re-examination of the development of the postotic portion of the human cranium and of the upper cervical segments. He agreed with the previously cited investigators except for the origin of the atlas:

A definitive vertebral segment is composed of the caudal sclerotome-half of one somitic segment together with the cranial sclerotome-half of the next succeeding segment. The occipital somites are concerned in the formation of the occipital bone. The atlas is formed from the caudal sclerotome-half of the first primitive cervical segment and the cranial sclerotome-half of the following segment. Consequently,

the cranial sclerotome-half of the first cervical segment, which contains the first cervical nerve, is left as a half segment (referred to as the proatlas).... In species other than Man, the proatlantal arch rudiments fuse either with the atlantal arch or with the occipital bone.

Sensenig comments on the segmentation of the occipital region:

DeBeer (1937) believes that nine segments participate in the formation of the skull. Of these, somites 6 through 9 are occipital, somite 5 becomes rudimentary, and the first four are involved in the formation of the preotic cranium.

On the basis of myotome counts in the 29-somite embryo, the first cervical artery defines the caudal boundary of the last occipital segment. In an adjacent section the primitive hypoglossal artery forms the cephalic boundary of this segment.... Rostral to the primitive hypoglossal artery, at least eight rootlets of the hypoglossal nerve can be identified. These unite into no less than three main roots and indicate three segments.

Therefore, on the basis of his thorough studies of the development of the occipito-cervical segments, Sensenig makes the following conclusions:

1. The most cephalic somite is the first to develop, and development of somites occurs in a caudal direction only.
2. Four occipital myotomes are identified.
3. Rootlets of the hypoglossal nerve are usually united into three to five roots.
4. The occipital bone is formed from at least four somites, with some indication that a fifth may be involved.
5. A definitive vertebra develops from the caudal sclerotome-half of one segment and the cranial sclerotome-half of the next succeeding segment. By this arrangement of the first cervical cranial sclerotome-half remains as a half segment between the occipital and atlantal rudiments, i.e. the proatlas.
6. This proatlantal primitive centrum forms the tip of the odontoid process; its arch rudiment assists in the formation of the occipital condyles.... It also assists in the formation of the alar ligaments as well as of the other ligaments of the occipito-atlantal joint.
7. The vertebral arch of the atlas separates from its respective primitive centrum, which forms part of the odontoid process. The atlantal rib rudiment is variable in degree of development and often incomplete.

8. The axis forms from the second definitive vertebral segment; its odontoid process represents the primitive centra of the atlas and the proatlantal half segment.

Gardner (1966) discussed the physiological changes of the developing neural tube and its influence on the skeletal counterparts:

The embryonal neural tube is a single cavity which constitutes the anlage of the ventricles and the central canal of the cord. Distention of this tube, that is, hydrocephalus and hydromyelia, is a normal state in embryonic life. This physiologic distention becomes compensated as the ventricular fluid filters through the attenuating rhombic roof to dissect open the subarachnoid space. If for any reason the roof of the fourth ventricle does not become adequately permeable during the critical sixth to eighth week period, a sufficient quantity of fluid will not filter through it to properly dissect open the developing subarachnoid space.... If hydrocephalus with hydromyelia is present in postnatal life, and particularly if the outlets of the fourth ventricle are found unperforated, as is true in many cases of syringomyelia, diastematomyelia, meningocele, and myelocoele, this represents not a new condition, but the pathological persistence of a state that is normal in the embryo.

Gardner indorsed the hydromyelic theory of Morgagni (1769) causing anomalous formation of the bony spinal column. Morgagni's initial observation was that "watery tumors of the vertebrae result from the pressure of fluid descending from the hydrocephalic head through the tube of the spine and pressing the bones asunder."

The diameter of the developing spinal canal of the embryo is determined by the diameter of the neural tube that it encloses (demonstrated by Holtzer, 1952). Holtzer found that "migrating precartilaginous cells respond in a discriminatory and stereotyped fashion to the presence of any neural tissue by maintaining a characteristic distance from the neural tissue. The precartilaginous cells are deployed in such a fashion that a lumen will eventually be formed in the cartilage whose size is a function of the enclosed nerve bundle." If transverse stretching of the precartilaginous sclerotomes occurs because of overdistention of the neural tube, these paired cell masses may fail to unite, not only posteriorly but anteriorly as well, resulting in combined anterior and posterior spina bifida (complete hemivertebrae). Furthermore, such transverse stretching of the sclerotomes will result in their longitudinal shortening and approximation so that these cell masses may coalesce longitudinally to form fused vertebrae. Thus, the stretching that interferes with normal fusion in the transverse axis of the spine may be accompanied by shortening with abnormal fusion (tethering) in its long axis.

As concluding remarks, Gardner stated:

The normally dilated central canal of the embryonic cord shrinks as the physiologic hydrocephalus becomes compensated. Because of this same compensatory process a pathologic overdilatation of the central canal may be reduced to normal. Despite such reduction the stretched sclerotomes having taken a set still may proceed to form a dilated spinal canal. Therefore, a spinal cord of normal diameter within a dilated canal is no indication that the cord was not overdilated in embryonic life. By the same token, a normal degree of dilatation of neural tube during the precartilaginous stage, followed by overdilatation at a later stage, may result in a hydromyelic spinal cord within a bony canal of normal diameter.

McRae (1971), in a radiology text, sums up the current thoughts and ideas concerning the embryology of the craniovertebral junction:

In the human embryo the postotic mesenchyme undergoes some degree of segmentation, with the appearance of somites.... The occipital somites do not develop like spinal somites. By the end of the third week of fetal life, four occipital somites have formed, but the first has already disappeared. In the remaining three somites the axial mesenchyme forms fairly typical sclerotomes, but soon fuse into one condensed mass unlike spinal sclerotomes.

At the level of the third occipital myotome, however, the axial mesenchyme usually divides into a pale-staining cephalic (anterior) and a dense-staining caudal (posterior) portion, somewhat like a spinal sclerotome. This sclerotome is called the third occipital or third hypoglossal sclerotome. The caudal dense portion develops extensions that resemble neural and chordal processes, but no costal processes. The pale cephalic part is in relation to the last hypoglossal nerve root. Normally the posterior dense part is not associated with the pale anterior half of the first spinal sclerotome, the proatlantal sclerotome. This dense portion remains continuous with the other tissue of its somite and with the rest of the basal plate of the anlage of the skull. Therefore, the atlanto-occipital joint is truly intersegmental unlike an intervertebral joint.

In the 14 mm. human embryo (gestation age about 40 days), the cartilage of the centrum of the atlas is connected with its cartilaginous arches by incompletely differentiated cartilage. Soon this poorly differentiated cartilage becomes transformed into dense blastemal tissue, in which the joints above and below the lateral masses of the atlas develop. The anlage of the body of this vertebra then separates from its arches. The anlage of the body of this vertebra, however, remains in close relation to the anlage of the body of the second cervical vertebra, because a normal intervertebral disk does not form between them.

During chondrification of the upper cervical vertebrae, there is a condensation of tissue on the ventral surface of each of the sclerotomes. These condensed transverse bands connect the ventral ends of

the blastemal neural processes; they are called hypochordal arches. They are all transitory except the first one, which is termed the hypochordal bow of the atlas. This hypochordal bow chondrifies at the time the arch of the first cervical vertebra separates from its body. The bow then joins the cartilaginous neural arch of the first cervical vertebra to form the cartilaginous atlas.

The first spinal somite is called the proatlantal or suboccipital somite, since the nerve of this somite supplies the suboccipital muscles. The cephalic half of this sclerotome does not unite with the occipital scleromere (half of a sclerotome in Man). It probably is the anlage of the tip of the odontoid process, since there is an inconstant secondary ossification center for the tip of the odontoid.... The main part of the odontoid process is formed from the first spinal sclerotome (proatlantal sclerotome) together with the anterior half of the second spinal sclerotome (the atlantal sclerotome).

The third occipital sclerotome has a caudal sclerotome with fairly well-developed neural and chordal processes. Incomplete incorporation of this sclerotome in the basiocciput is considered the cause of manifestation of an occipital vertebra or vertebralization of the occiput. The bony parts involved are below the hypoglossal foramen.

In occipitalization of the atlas, the hypochordal arch of the atlas with its attached neural arches becomes continuous with the occipital cartilage. In spite of this, the centrum of the atlas fuses with the centrum of the axis, and they separate themselves from the hypochordal bow but remain attached to the arch of the axis. In from one third to one half of patients with occipitalization of the atlas, the second and third cervical vertebrae fuse both in the bodies and in the arches.

### Neurological Considerations

To establish the relative clinical importance of atlanto-occipital fusion, the following comments and excerpts pertaining to neurological disorders and deficits of this anomaly are reported.

Bezi (1931) discusses assimilation of the atlas as related to compression of the medulla:

Among the pathologic changes of bones which may cause compression of the medulla, the dislocation of the odontoid process of the axis seems to be most important.... According to my observation, the odontoid process may become "dislocated" in consequence of an assimilation of the atlas, and may cause compression of the medulla. But it seems that the assimilation must reach a certain degree, while the mass of the atlas remains underdeveloped. Thus assimilation of the atlas causes pathologic changes, owing to the abnormal mechanical-static conditions.

As to the compression of the medulla, the alterations of the articulations are of great importance. By their successive development, the volume of the bone-walled channel around the medulla is changed accordingly, and in this way a vicious cycle arises between compression and the conditions of the joint.... A lethal compression of the medulla may occur when the odontoid process is dislocated at least from 7 to 10 mm. backward, and from 18 to 25 mm. upward. In considering compression, the development of hydrocephalus and hydromyelocele is of great importance.

Bezi also mentions a possible relationship of occipito-cervical fusion with epilepsy:

Another pathologically important feature of a union of the atlas with the occipital bone was pointed out by Anton. He found nine cases of epilepsy among thirty-one persons showing "eine Verwachsung oder ganz nahe Kontinuität des Atlas mit dem Hinterhauptbeine am Profilröntgenbilde" (a fusion or complete continuity of the atlas with the occipital bone in the profile radiograph).

However, Bezi is in agreement with other investigators of that era in regards to an etiology of epilepsy: "The observations made to date do not seem to have proved definitely the pathologic importance of assimilation of the atlas."

List (1941) thoroughly discusses the neurological syndromes associated with occipito-vertebral junction developmental anomalies:

With increasing experience, it has been realized that developmental deformities of the occipital bone, atlas, and axis are frequently associated with characteristic neurologic syndromes.... Three mechanisms may be responsible for the neurologic signs: (1) They may be produced by bony deformity causing mechanical compression of the neuraxis. (2) The neurologic syndrome may be the result of an associated, though independent, malformation of the nervous system and not a direct consequence of the bony lesion. (3) Finally, the clinical picture may result from the combination of the two foregoing mechanisms.

When the atlas is fused with occiput, the odontoid process frequently is malformed or hypoplastic, or its ligaments are absent. An abnormal transverse ligament, especially, permits pathologic mobility of the dens. Consequently, the odontoid process tends to separate from the anterior arch of the atlas and, thus by its posterior dislocation, narrows the neural canal. When the atlas is firmly united with the skull, the force of gravity appears to increase this dislocation, as the assimilated atlas tends to slide farther forward on the axis. The malformed posterior arch of the atlas may also be slightly displaced upward and anteriorly, so that it lies within the foramen magnum and in front of the posterior rim of the latter. The result of all these changes is a definite narrowing of the neural canal at the foraminal level, with the medulla or uppermost cervical part of the cord wedged between the posteriorly (and upward) dislocated dens and the posterior rim of the foramen magnum (or posterior arch of the atlas).

The clinical picture, therefore, is mainly that of high cervical compression with slight, or more often without, involvement of cranial nerves. Only the spinal accessory nerve may be damaged. A combination of mild tetraparesis with ataxia and nystagmus is characteristic of the moderately advanced forms; hence it is not surprising that occasionally the erroneous diagnosis of multiple sclerosis or cerebellar heredoataxia is made. As a rule, muscle tone is only slightly increased, but the deep reflexes are markedly exaggerated, and signs referable to the pyramidal tracts are present. Pareses are usually mild and are more pronounced in the lower extremities. The same is true for the ataxia, which has the character of cerebellar incoordination rather than that of a disturbance of the posterior columns. Objective changes of sensation are rarely demonstrable, or are slight.

With advanced lesions the neurologic picture approximates the syndrome of severe transverse lesion of the high cervical portion of the cord. A high degree of spastic tetraparesis is found. All deep reflexes, including those of muscles supplied by the upper cervical segments, are increased. Hoffman's sign may be exaggerated to a finger clonus, and one may be able to demonstrate a cutaneous palmar response analogous to the Babinski phenomenon of the foot, viz., Juster's reflex.

Interesting are various reflex synergias which in these cases can be elicited by nociceptive cutaneous stimulation below the level of the lesion.

Of unusual interest are the disturbances of respiration associated with advanced lesions. The high site of compression causes bilateral supranuclear paresis of respiratory muscles. Forceful volitional breathing is accomplished mainly by auxiliary muscles, such as the sternocleidomastoids, the scaleni, the levatores scapulae and the muscles supplied by the ansa hypoglossi. During quiet spontaneous (automatic) respiration the diaphragm still shows considerable function, whereas the intercostal muscles may be completely paralyzed.

Even in cases of the most advanced lesions, sensory function is surprisingly little disturbed. The spinothalamic qualities of pain and temperature may be practically normal, whereas the sensations mediated by the posterior columns show some impairment. Evidently, the posterior columns are more exposed to direct bony pressure than are the anterolateral tracts. A level may be demonstrable only for vibratory sensation and the ability to recognize skin writing.

The syndrome of high cervical compression is completed by vegetative disorders, such as supranuclear paresis of the bladder and rectum, absence of thermoregulatory sweating and cephalic pilomotor response over the entire body and a tendency to tachycardia.

In contrast to basilar impression (which is discussed in another section), dislocation of the atlas on the axis rarely produces complete block of the foramen magnum with subsequent development of intracranial hypertension. Mild foraminal obstruction, however, may occur and can be recognized by subjective symptoms, such as headaches and dizziness on exertion. The presence of nystagmus also possibly indicates interference with the circulation of cerebrospinal fluid at the foramen. Necropsy in such cases may reveal internal hydrocephalus and dilatation of the lateral pontile cisterns. On the other hand, lumbar puncture shows that interference with the circulation of cerebrospinal fluid is not severe.

List also comments on the question, could narrowing of the foramen magnum and compression of the medulla account for the comparative frequency of convulsive attacks.

A critical review of Solbrig's observations in 10 cases revealed that there was definite bony encroachment on the medulla in only 4 instances. It is conceivable that temporary interference with the blood supply of the brain stem, caused by compression or stretching of the vertebral and basilar arteries, may be a factor in the causation of convulsive seizures.

In regards to the causes of the neurological syndrome associated with atlanto-occipital fusion and its differential diagnoses, Hadley (1948) writes:

Neurological signs are not present in all cases visualized by the roentgen ray. In congenital cases, for some unknown reason, the first symptoms are likely to appear as late as the second or third decade but may be progressive and even fatal. They are caused by: (1) constriction of the foramen with resultant pressure upon nervous structures; (2) adhesions; (3) ischemia from interference with blood supply; (4) interference with the dynamics of the cerebrospinal fluid between the ventricles and subarachnoid spaces causing hydrocephalus; and (5) increased pressure within the cerebellar fossa from basilar impression or invagination.

Neurological symptoms (of atlanto-occipital fusion), if present, may be mistakenly diagnosed as indicating multiple sclerosis, spastic paralysis, amyotrophic lateral sclerosis, cerebellar or upper cervical tumor, Klippel-Feil syndrome, hydrocephalus, or syringomyelia. In fact, the last two may coexist with basilar impression.

Hadley encourages early diagnosis and surgical treatment for those individuals with neuropathies induced by atlanto-occipital fusion.

A suboccipital decompression operation with upper cervical laminectomy and opening of the dura is indicated in an attempt to arrest the progressive compression and destruction of nerve tissue. Of course, restoration of normal bone relations or destroyed nervous tissue is impossible. Fusion should be done if the atlas was dislocated.

Since early decompression of the foramen and upper cervical region offers some hope of arresting the destructive process in the central nervous system, a lateral survey roentgenogram of the upper cervical spine made in full forward flexion is indicated in all cases showing neurological symptoms of upper cord degeneration or compression.... If the arch of the atlas is not fused to the occiput, it will separate from that bone in this position. A similar lateral survey film should be taken in all cases of torticollis or asymmetry of the head and neck.

McRae (1953), during a review of radiographic findings in syringomyelia and syringobulbia at the Montreal Neurological Institute, "found that 38% of the patients had bony abnormalities in the region of the foramen magnum." A study was undertaken to try to correlate anatomic findings with neurological signs and symptoms.

The most significant findings were related to the odontoid process of the axis. If the odontoid was excessively long or unusually high in position, or if it was angulated posteriorly, symptoms and signs were

usually found. If the anteroposterior diameter of the spinal canal behind the odontoid process was 19 mm. or less, there was always neurologic signs. If the odontoid process moved back and forth more than 3 mm. on flexion and extension of the head, neurologic signs were always present. In the two cases of occipitalization of the atlas that came to autopsy, there was a depression in the anterior surface of the medulla oblongata into which the odontoid projected. In fifteen of the twenty-eight cases, the odontoid process lay more than 3 mm. behind the anterior arch of the atlas; and, in most cases, this was the reason why the antero-posterior diameter of the spinal canal was reduced at this level. In these cases, and also in some of the others, the antero-posterior diameter of the spinal canal at the level of the odontoid was reduced by a bony fringe projecting inwards and downwards from the posterior lip of the foramen magnum. This bony fringe represented an assimilated posterior arch of the atlas. The second and third cervical vertebrae were fused in eighteen of the twenty-eight cases, but this did not seem to be of any clinical significance.

For occipitalization of the atlas, McRae reports that "the average age at which symptoms appeared was 31 years" with a range of 7 - 45 years of age. "The neurologic symptoms and signs often appeared after a head or neck injury; yet in none of these patients was a fracture shown."

Neurologic symptoms seemed to be due to the occipitalization of the atlas in nineteen of the twenty-eight cases. Weakness or ataxia of the legs was the most frequent complaint, occurring in fourteen patients. Numbness and/or pain in the extremities was the next most frequent symptom, in eleven cases being situated in the arms and in four in the legs (these four also had numbness and pain in the arms). Dull aching pain in the occiput or upper neck was noted in eleven cases, but there was never any pain of root character, nor was there hyperaesthesia or hypaesthesia in the second cervical dermatome.

Neurologic signs were found in seventeen cases, usually in the motor system (hyperreflexia, Babinski and Hoffman signs, weakness, etc.). Motor signs were encountered in the arms and legs in thirteen patients, and in the arms alone in two patients. Ataxia was frequent and occasionally very severe. Posterior column signs were present in the arms and legs of eight cases and in the arms alone in four. Six patients showed reduction of two-point discrimination or stereognosis in the hands, and two patients had similar signs in the feet. Four patients had considerable loss of pain sensation in the hands. Six cases had slight generalized reduction in sensation in the upper extremities and four in the lower extremities. Two patients presented Horner's syndrome. Nystagmus occurred in nine.

Eight of the patients with occipitalization of the atlas were considered to have no symptoms or signs referable to this condition. In three of the patients with occipitalization of the atlas, it was not

possible to say whether or not there were neurologic symptoms or signs due to this lesion (because other organic lesions coexisted).

A summary of McRae's observations is provided in the following table:

Occipitalization of the Atlas

28 Cases: 22 male, 6 female

<u>Neurologic Symptoms in 19 Cases</u>		<u>Neurologic Signs in 17 Cases</u>	
Weakness and ataxia - legs	14	Long tract deficit - arms	13
Weakness and ataxia - arms	10	Long tract deficit - legs	11
Weakness and ataxia - both	9	Ataxia - arms	7
Numbness and pain - arms	11	Ataxia - legs	6
Numbness and pain - legs	4	Nystagmus	9
Numbness and pain - both	4	Bulbar signs	6
Headache	11	Posterior column defect - arms	4
Neck pain	7	Posterior column defect - legs	8
Visual symptoms	7	Two-point loss/astereognosis - arms	6
Auditory symptoms	5	Two-point loss/astereognosis - legs	2

In the same year McRae and Barnum (1953) collaborated on a report of 25 patients with occipitalization of the atlas. It must be assumed that the neurological data presented was taken from the same or similar patient sampling, used in the previously cited paper by McRae (1953) alone. Of the 25 patients, 18 demonstrated neurologic symptoms and/or signs; seven were asymptomatic. The distribution of signs and symptoms were similar to the previously cited article. Pertinent items of note from McRae and Barnum (1953) follow:

There has been some question in our minds as to whether assimilation of the atlas in itself is ever productive of symptoms or signs without encroachment upon the bulb or cord by associated soft deformities or bony malformations. The most frequent of the latter was a posteriorly displaced odontoid process of the axis which occurred in 15 of 25

cases (60 per cent of the time) and in 12 of 18 cases who had symptoms thought to be attributable to cervical abnormality. Our definition of posterior displacement is a dens lying 4 mm. or more posterior to the anterior arch of the atlas.... The important consideration is, of course, the amount of space available to the cord as measured from the posterior surface of the dens to the posterior border of the foramen magnum, or other closest posterior bony point.... It is possible to say that, if the bony spinal canal at the level of the dens is 19 mm. or less in antero-posterior diameter, the patient is probably having signs due to the bony abnormality. When the head is flexed, this space may be 1 to 5 mm. smaller.

Another frequent finding was a thickened band of dura posteriorly (usually at the junction of the occipital bone and the spine) which constricted the cord, in one instance to a degree sufficient to obliterate its normal pulsations, these returning only after dissection away of the band. Thickened dural bands were noted in 4 of the 12 cases which were surgically explored. Also notable was the association of cerebellar tonsil herniations with the cases of assimilation of the atlas, this finding being present in 3 of the 12 cases where it was either seen surgically or by air encephalography.

McRae and Barnum related that seven of their 18 symptomatic cases (38.9%) were previously misdiagnosed; by far, the most frequent diagnosis was multiple sclerosis. "A glance at the above syndrome immediately recalls the similarity to multiple sclerosis, especially with the evidence of fluctuation in the intensity of the signs and symptoms in some cases."

Spillane, Pallis and Jones (1957) studied 24 neurologically disabled patients with bony and/or neural developmental anomalies of the foramen magnum, seven of which had occipitalization of the atlas. They state:

Perhaps the most interesting feature about them (developmental anomalies found in the region of the foramen magnum) is their diversity; each type may vary in degree, in its clinical effects, and in the pattern of its association with other neural or skeletal defects in the neighbourhood.

Excerpts of pertinent information taken from Spillane et al. concerning the neurologic syndrome of defects at the region of the foramen magnum, associated Klippel-Feil syndrome, and relationships with syringomyelia are presented:

Occipitalization of the atlas may be asymptomatic. It is likely to be associated with other skeletal anomalies at the cranio-vertebral junction and with neurological disability.... In cases of synostosis of the atlas (occipitalization), the neurological disorder is equally variable, and dural bands or cerebellar displacement may be revealed at operation, in addition to the more commonly found dislocation of the odontoid.

The pathological processes found at operation to be responsible for a given syndrome may differ. Clinical syringomyelia in a patient with a skeletal anomaly at the cranio-vertebral junction may result from intramedullary cavitation (representing true syringomyelia, hydro-myelia, or ischaemic necrosis) or from compression of the neuraxis (by a stenosed foramen magnum, a displaced odontoid, a dural band or by cerebellar "herniation").

It would appear "(a) that a narrow spinal canal ( $\leq 19$  mm. at the level of the atlas) can be found without long tract signs; (b) that when atlanto-axial dislocation is the cause of such canal narrowing, neurological signs often occur."

The variable repercussions of a narrow spinal canal, at the level of the atlas, could be accounted for by differences, in different patients, in the size of the enclosed cord or in the pattern of its blood supply, or by the known occurrence, in certain of these cases, of dural bands or other structural abnormalities of the soft tissues not demonstrable by radiography, yet capable of causing cord compression. It is probable, moreover, that intermittent narrowing of the spinal canal, such as presumably occurs in cases of atlanto-axial dislocation, is more harmful to the cord than narrowing not liable to such repeated variations.

Fusion of cervical vertebrae is usually symptomless; the C<sub>2</sub>-C<sub>3</sub> level is the commonest site of fusion. Patients with fused cervical vertebrae and no other anomaly may develop tetraplegia following minor trauma. When chronic neurological disability is present, fusion of cervical vertebrae is probably never the sole anomaly; there is usually a bony defect at the level of the foramen magnum (basilar impression, occipitalization of the atlas or atlanto-axial dislocation).

In the Klippel-Feil syndrome (congenital cervical synostosis) the fusion of cervical vertebrae may be the only defect, or it may be associated with basilar impression or occipitalization of the atlas. Some of those affected may show little disability despite gross bony deformity; others may develop spastic paraplegia, syringomyelia or hydrocephalus. Cerebellar ectopia may be demonstrated in some cases.

From a study of case reports and radiographs which have been published from time to time, it is possible to say that neurological complications do arise in the Klippel-Feil syndrome; they are not directly due

to the fused cervical vertebrae, but to associated bony or neural malformations at the cranio-vertebral junction.

Anomalies of the cranio-vertebral junction are common in patients with syringomyelia. The relationship is rarely one of cause and effect; in the majority of instances, the neural and skeletal defects are associated malformations.

It has long been known that anomalies of the spinal cord and vertebral column may occur in various combinations. In the so-called dysraphic disorders there is defective fusion of tissues in the dorsal medial region of the developing embryo. Cutaneous, mesodermal and neural malformations in the longitudinal plane occur. It is possible that true syringomyelia arises from a process of neural dysraphia. In syringomyelia there may also be defects at the cranio-vertebral junction. These frequently take the form of some disturbance in the transverse plane, such as anomalous segmentation.... Garcin and Oeconomos reviewed 112 case reports (published between 1901 and 1951) of various cranio-vertebral anomalies associated with neurological signs and found that a syringomyelic syndrome was present in 14.3 per cent of the cases. When occipitalization of the atlas was present, the incidence of syringomyelia approached 25 per cent.

Interesting signs that may be found in patients with cranio-vertebral anomalies are (1) postural loss confined to the upper limbs, (2) spontaneous vertical nystagmus (with oscillopsia), (3) mirror movements of the hands. (The latter two neurological signs are associated principally with cerebellar ectopia and Klippel-Feil syndrome respectively.)

The basis of the symptom (postural loss solely in the upper limb) must be sought in the anatomical disposition of abnormal susceptibility to compression, in the upper cervical cord, of those fibres conveying proprioceptive sensation from the upper limbs. Although this is not a common pattern of sensory loss, it has been observed in compressive lesions at the level of the foramen magnum and was a conspicuous feature in 5 of the 7 patients reported by Symonds et al. (1937). These authors thought that defective posterior column sensibility practically confined to the upper limbs "may be a characteristic feature of compression of the cord at this (foramen magnum) level at certain stages of its development."

McRae and Barnum, on the other hand, found posterior column signs infrequently and suggested "that the main damage to the cord was occurring anteriorly, presumably by the displaced odontoid process of the axis, rather than posteriorly by the dural band. Not all the cases showing posterior column signs had a dural band or cerebellar tonsillar herniation posteriorly."

Epstein (1962), in his text, gives a cursory overview of the neuro-logic disturbances related to atlanto-occipital fusion:

In the event of complete fusion, no symptoms appear. However, partial fusion may be associated with instability of the atlas and axis, abnormal mobility of the odontoid being produced by lack of fixation of the ligaments, particularly the transverse ligament. This abnormal range of motion can be demonstrated on lateral roentgenograms in flexion and extension, and are better seen on laminagrams. Because of impingement of the bony structures on adjacent nerves and the spinal cord, a wide range of neurologic symptoms may appear, together with pain, abnormal attitudes of the head and limited ranges of motion. Neurologically these symptoms often mimic those of various degenerative diseases, such as syringomyelia and multiple sclerosis. Weakness of the lower extremities and ataxia may be presenting symptoms, alone or together with concomitant sensory disturbances. Often motor impairment of the upper extremities also appears.

Bharucha and Dastur (1964) present a clinically oriented paper of forty patients with neurological symptoms arising from skeletal anomalies of the craniovertebral junction. They emphasize the neurologic presentation of the patients and treatment employed. The distribution of the skeletal anomalies consists of 23 cases of occipitalization of the atlas, 4 cases of atlanto-axial dislocation with odontoid separate, 6 cases of atlanto-axial dislocation with odontoid intact, 6 cases of basilar invagination, and one case of an unassimilated rudimentary atlas.

The neurological deficits of this group of patients are as follows:

Cranial nerve signs were present in 4 cases of occipitalization; 2 had corneal anaesthesia with palatal weakness and dysphagia, one of these having, in addition, diminution of pain and temperature sensibility in the face; 1 had dysphagia and 1 had sensory loss in the trigeminal area on one side. Two cases of atlanto-axial dislocation had bilateral palatal weakness with one of them having, in addition, a sixth nerve palsy. Five cases of basilar invagination had abnormal cranial nerve signs. In 2 there was loss of corneal sensation; 2 had palatal weakness and one of these had, in addition, deafness and unilateral vocal cord paralysis; 1 had loss of corneal sensation, bilateral palatal weakness and hoarseness of voice.... A Horner's syndrome was present in 4 cases of occipitalization and 2 of dislocation. Nystagmus was observed in 11 cases of occipitalization, 4 of dislocation and 5 of basilar invagination.

Pyramidal signs were present in 21 cases of occipitalization and in all cases of the remaining groups. Wasting was present in 5 cases of occipitalization, 4 of dislocation and 2 of basilar invagination.... Ataxia was present in 11 cases of occipitalization, 4 of dislocation and 4 of basilar invagination. In occipitalization and basilar

invagination, it tended to be more severe and generalized than in dislocation, where it was often confined to one arm.

Loss of position sense was the most common form of objective sensory loss (occipitalization 15, dislocation 7, basilar invagination 4, rudimentary atlas 1). The upper limbs were affected in every case, but a combined affection of upper and lower limbs was also observed (occipitalization 7, dislocation 3, basilar invagination 1). Vibration sense was impaired in 4 cases of occipitalization, 2 of dislocation and one each of basilar invagination and rudimentary atlas. Vibration loss to a level on the trunk was present in both cases of dislocation and in one case of occipitalization where the odontoid was abnormally mobile due to laxity of the transverse ligament.

Three patterns of cutaneous loss were observed--loss to a transverse level on the trunk (occipitalization 3, dislocation 1), loss in one limb (occipitalization 5, dislocation 2, basilar invagination 1), and loss in glove and stocking distribution (dislocation 1, basilar invagination 1). Dissociated sensory loss was present in 7 cases (occipitalization 4, dislocation 2, basilar invagination 1). In all, excepting one, where it was symmetrically present in the palms, it was confined to one upper limb, at times extending to the chest or face on the same side. It was significant that, in these cases, there was wasting of muscles in the affected limbs.

Sphincter disturbances occurred in 10 cases (occipitalization 5, dislocation 3, basilar invagination, rudimentary atlas 1)... Respiratory weakness was present in 5 cases (occipitalization 2, dislocation 3).

In one case of occipitalization of the atlas, fusion of C<sub>2</sub>-C<sub>3</sub>, and abnormally lax transverse ligament, "there was no demonstrable abnormality in the nervous system." Unusual clinical features were observed in 4 cases of occipitalization of the atlas. Case 1 "presented with a clinical picture suggestive of occlusion of one posterior inferior cerebellar artery." Case 2 "had vertigo, vomiting, severe ataxia and sensory loss over the left arm and chest, suggestive of a brain-stem vascular disturbance." Case 3 (a thirteen year old girl) "had been observed to perform mirror-movements of her left arm identical to those of the right, ever since childhood." Case 4 "complained of black spots before his eyes whenever his neck was compressed."

In a review of radiographic materials, Bharucha and Dastur make the following observations:

In all our cases of occipitalization and atlanto-axial dislocation, and this case of rudimentary atlas, the distance between the posterior surface of the odontoid and either the posterior arch of atlas, or the dorsal rim of the foramen magnum, was reduced considerably beyond the safety limit of 19 mm. during flexion of the head.... Myelography, in the majority of instances (of occipitalization), showed a partial block at the level of the foramen magnum.

Bharucha and Dastur describe the modes of treatment:

Twenty patients were treated conservatively and 20 by surgery. Conservative treatment consisted of immobilization in a plaster of Paris, felt or plastic collar and was carried out in 14 cases of occipitalization, 4 of dislocation and 2 of basilar invagination. Full recoveries were obtained in the case of occipitalization with posterior inferior cerebellar artery syndrome, the case of occipitalization with fused C<sub>2</sub>-C<sub>3</sub>, who developed torticollis with restricted neck movements following rheumatic fever (the child without neurological deficits previously mentioned), and a case of atlanto-axial dislocation with odontoid intact who had mild initial symptoms. Improvement was recorded in only 3 other cases (all having occipitalization); the rest remained static.

The aim of surgical treatment has been to restore the angulated and compressed dura to its normal shape and thereby decompress the medulla and cord. In occipitalization and basilar invagination decompressive measures did produce some very gratifying results.

The operated cases were occipitalization 9, atlanto-axial dislocation 6, basilar invagination 4, and rudimentary atlas 1. The treatment for occipitalization was suboccipital craniectomy, for atlanto-axial dislocation and rudimentary atlas excision of the posterior arch of the atlas, and for basilar invagination suboccipital craniectomy again, and when required, combined with excision of the posterior arch of the atlas. The only exceptions were two cases, both having occipitalization; in both decompressive cervical laminectomies were performed, in the former for obstruction at fused C<sub>2</sub>-C<sub>3</sub> vertebrae (Klippel-Feil) and in the latter for obstruction between C<sub>2</sub> and C<sub>5</sub>, due to vertebral canal encroachment from Albers-Schönberg's disease; the former improved, while the latter recovered fully.

Full recoveries were also recorded in 3 cases of occipitalization and 3 cases of basilar invagination; 3 cases of occipitalization were much improved.... There were 4 deaths. There was 1 death in 9 cases of occipitalization and 3 deaths in 6 cases of atlanto-axial dislocation.

In conclusion, our impression is that foramen magnum decompression is an adequate procedure for occipitalization and basilar invagination, but there must be a better solution for the more advanced type of atlanto-axial dislocation.

McRae (1969) makes some general comments concerning the neurologic picture of those patients with bony abnormalities at the cranio-spinal junction:

Certain bony abnormalities at the cranio-spinal junction frequently produce neurological symptoms and signs. However, the symptoms and signs are sometimes thought to indicate lesions at other levels in the central nervous system or lesions of a different nature.... The cause of symptoms was chronic or recurrent pressure on the lower medulla oblongata or upper cervical cord. The pressure may come from all directions, as in basilar invagination. More often, it comes mainly or entirely from in front, from the odontoid process.

Different diagnoses were suggested by different physicians who saw the patient at different stages in his disease:

Referring Diagnoses in 68 Cases of Bony Abnormalities at the Cranio-Spinal Junction

Multiple sclerosis	31
Syringomyelia or syringobulbia	18
Brain stem or posterior fossa tumor	16
Foramen magnum lesion or Arnold-Chiari malformation	13
Cervical fracture or dislocation or cervical disc protrusion	9
Degenerative disease of cord	6
Cerebellar degeneration	4
Hysteria	3
Lead poisoning (chronic)	1

For many of these conditions, no curative treatment exists at the present time. However, bony abnormalities at the cranio-spinal junction are amenable to surgical treatment, which, in most cases, arrests the progress of the disease and, in some cases, results in a return to normal.

Almost half of our patients with symptoms due to bony abnormalities of the cranio-spinal junction had multiple lesions.... The most common was a combination of occipitalization of the atlas with basilar invagination.

Tables, summarizing the symptoms and signs of a large number of patients, do not describe adequately certain syndromes that occur within such a group. A number of the patients with these bony anomalies had occipital or suboccipital pain of a very characteristic type. It was described as a bursting type of headache, usually precipitated by inadvertently flexing the neck or stooping forward. In most cases, if the patient immediately lay down, the pain would go away; but, if this was not possible, the headache would become violent and persistent and often would be followed by nausea and vomiting.

Several of the patients had had difficulty with their legs since childhood or adolescence.... Several of the patients gave a history

of multiple episodes of quadriplegia. It was usually described as a feeling of weakness and was not recognized as quadriplegia.... Exacerbations and remissions were common, but remissions almost always occurred when the patient was confined to bed. If some form of medicinal therapy was being given at the time, the remission was usually attributed to the medicine rather than to the bed rest.

Commenting more specifically to occipitalization of the atlas, McRae offers the following:

In occipitalization of the atlas, the odontoid process is often high in position, lying within the effective foramen magnum and competing with the medulla oblongata for space. (The fused atlas becomes the effective foramen magnum.) When the distance between the odontoid process and the posterior margin of the effective foramen magnum was less than 19 mm., all of the patients in the series had neurological signs. The measurement must be made with the head flexed. When these patients flex and extend the head, the odontoid process moves backward and forward, a type of atlanto-axial dislocation.

Because the axis and atlas are abnormally close to the skull in occipitalization of the atlas, it is the lower medulla oblongata rather than the upper cervical cord that usually is squeezed. At autopsy, there is usually a depression on the ventral surface of the medulla oblongata opposite the odontoid process. Some of these patients have a dural band across the posterior lip of the effective foramen magnum, exerting counterpressure on the posterior aspect of the medulla. In occipitalization of the atlas, the cerebellar tonsils often lie within the effective foramen magnum and show gliosis and adhesions.

Appleby (1969) is mainly interested in the nervous system anomalies at the craniovertebral junction, irrespective of whether or not a bony anomaly coexisted. Of 30 patients who presented with some form of "foramen magnum syndrome," 27 proved to have some form of hind brain descent. Of these 27 patients, 3 cases of occipitovertebral fusion were present. There were also 3 cases of congenital C<sub>2</sub>-C<sub>3</sub> fusion. One of the 3 patients without evidence of hind brain descent was a case of occipitalization of the atlas with a narrow foramen magnum.

Appleby comments on the etiology and pathogenesis of syringomyelia:

Many cases presenting as typical or atypical syringomyelia have their origin in anomalies of the hind brain described by Chiari--which may or may not be accompanied by bony abnormality. Further, these anomalies may themselves produce arachnoiditis.

Gardner (1965) postulated that most, if not all, cases of syringomyelia are the result of longstanding hydromyelia. This latter he believes to be due to a congenital anomaly, resulting from incomplete perforation of the rhombic roof in the 6th to the 8th gestational week. This, he says, results in obstruction to the outflow of cerebrospinal fluid from the fourth ventricle and subsequent dilatation of the central canal. The syrinx, unconnected with the obliterated central canal, is produced by dissection of the pulsating fluid, the cavity so formed being later isolated by gliosis and fibrosis.

Gardner's hypothesis, while explaining syringomyelia, explains neither those cases presenting as clinical syringomyelia without evidence radiographically or at operation of a syrinx, nor the 3 cases in our series who were shown to have normal entry or egress of contrast medium from the fourth ventricle.

In a radiology text of the skull and brain, McRae (1971) discusses the anomalies of the craniovertebral junction, primarily from a radiographic, diagnostic point of view. In general terms, he summarizes the neurologic significance of these malformations:

Abnormalities at the craniovertebral junction may involve only the bones and joints or only the meninges and nervous system, or both systems together. Some congenital anomalies of bones and joints in this region may not be associated with congenital anomalies of the meninges and central nervous system, yet may gradually lead to pressure on them, either directly or indirectly, and cause secondary lesions of the central nervous system.

The age varies at which symptoms result from congenital abnormalities at the craniovertebral junction, depending to some extent on the type of lesion. In patients with the Chiari malformation, symptoms usually develop at birth or in early life and usually present little difficulty in diagnosis.

Developmental abnormalities of the brain or meninges, or of both, in the region of the craniovertebral junction usually cause hydrocephalus in early life. When congenital anomalies of the brain or meninges at the craniovertebral junction do not produce symptoms until adolescence or adult life, the clinical signs vary. In some of these patients, symptoms of low-grade increase in intracranial pressure are present. In other patients there is evidence of slowly progressive cerebellar or brainstem syndromes, often with long-tract signs in the lower extremities. In still another group, spinal cord signs may predominate, but these usually are associated with a bony anomaly.

Congenital anomalies of the bones and joints of the craniovertebral junction, unassociated with brain or meningeal anomalies, most often produce no neurologic symptoms and signs until adult life. At that time spinal cord signs and symptoms may appear. These result from

pressure on the upper cervical cord or lower medulla oblongata or from the presence of syringomyelia. The average age of onset of symptoms in such patients is 28 years.

These lesions may be misdiagnosed as multiple sclerosis, primary syringomyelia, or even disk disease. In congenital bone and joint lesions the symptoms may be pronounced in the lower extremities. When they are minimal or absent in the upper extremities, early examination of the cervical region in the search for etiologic factors may be neglected.

McRae comments more specifically to the cause of neurologic signs and symptoms of patients with an atlas assimilated into the occiput:

The assimilated posterior arch is often incomplete posteriorly, whether or not it is fused to the posterior edge of the foramen. These bony protuberances on the foramen magnum may not reduce its size, but there is often a thick band of dura at the level of the assimilated posterior arch. The band presses against the posterior surface of the medulla oblongata, preventing the medulla from moving away from the odontoid process.

When the atlas is occipitalized, the head no longer flexes and extends at the atlanto-occipital joint. Instead these movements must take place at the atlantoaxial joints. If the transverse ligament of the atlas has developed poorly or become stretched, atlantoaxial dislocation will occur during flexion. Frequently in these instances neurologic symptoms and signs develop. Of course, the transverse ligament of the atlas may hold the odontoid process against the assimilated anterior arch. In that case no atlantoaxial dislocation occurs, and seldom, if ever, are there symptoms.

### Basilar Impression, Invagination and Platybasia

A developmental anomaly of the occipital bone called basilar impression or invagination, and by some investigators platybasia, is presented. The anatomical description of this abnormality, its neurological significance, and its relationship to occipitalization of the atlas are reviewed. Diagnostic criteria based on measurements of skull and radiographic material are reported.

Chamberlain (1939) presents the morphologic changes and the clinical importance of basilar impression:

"Basilar impression" is an unusual but important developmental anomaly of the occipital bone and upper cervical vertebrae. Its diagnosis during life rests upon recognition of the characteristic stenosis of the foramen magnum and cephalic bulging of the clivus and neighboring bony structures into the posterior fossa of the cranium. Its chief importance lies in its effects, sometimes profound, upon the central nervous system, especially as these effects may be obviated by appropriate surgical procedures.

The morphologic changes shown by roentgenograms give the impression of softening of the base of the skull and moulding through the force of gravity. It is as though the weight of the head has caused the ears to approach the shoulders, while the cervical spine, refusing to be shortened, has pushed the floor of the posterior fossa upward into the brain space.

Varying degrees of fusion or assimilation of atlas into occiput are met with, as might be expected from a consideration of the embryology of these parts. In some cases the atlas has lost its identity completely. In others it is fused with the margin of the foramen magnum on one side or the other, or the ventral part of the vertebra is fused with the ventral margin of the foramen while the neural arch is defective.

The effects of the deformity upon the nervous system may be slight or profound. There is a marked tendency for these nervous manifestations to be progressive. In a certain number of cases, they ultimately become the cause of death in the third, fourth, or fifth decade, though the patient may not have exhibited any nervous manifestations during the first few years of life. This has led a number of observers to conclude that the deformity itself is increasing, and must therefore be on an osteomalacic or rachitic basis rather than on the basis of a developmental anomaly. Dr. Richard U. Light has called my attention to the possibility of a better explanation, namely, that when skeletal growth takes its characteristic and normal spurt in the

years just preceding puberty, the spinal cord has already attained its normal adult length. The increase in the length of the spine may produce a certain amount of traction on the cord and, in cases of "basilar impression," deleterious degrees of pressure of the odontoid process against the medulla may begin at this period of skeletal growth.

Since indications of osteitis, rickets, osteomalacia, etc. are entirely absent, the striking tendency for the patient to escape neurologic effects during the first decade or so of his life, and then to develop a markedly progressive symptomatology, must be accounted for on some other basis. We offer the thought that the young developing brain and brain stem may be able to tolerate compressive effects which later prove deleterious to older tissues. In our autopsied case and in many other cases that have been thoroughly studied, the flattening, softening, and atrophy of the medulla at the point of impingement of the abnormally located odontoid process have been striking. Yet we have reason to believe that the odontoid impinged in more or less the same degree during earlier years, before the onset of recognizable neurologic symptoms and signs.

The neurologic manifestations of basilar impression are most often such as to simulate syringomyelia, though disseminated sclerosis and various types of spastic paralysis may also be imitated, according to the particular tracts, columns, or other parts of the central nervous system that are effectively impinged upon or otherwise disturbed by the skeletal deformity.

Schüller (1911) reported the first case diagnosed during life (by roentgen examination, of course). He thoroughly understood the effects of the deformity upon the nervous system and presented clinical examples of (1) paralysis and irritation of cranial nerves (vagus, hypoglossal, etc.); (2) compression of cerebellum against the tentorium, with even a block of the aqueduct of Sylvius; (3) local pressure effects upon the medulla by the odontoid process and the stenotic foramen magnum.

As an aid in the diagnosis of basilar impression, Chamberlain paid close attention to the relationships of the clivus, atlas, and odontoid process of the axis on the conventional lateral radiographic projection of the skull. He noted: "By drawing a 'base line' from the dorsal lip of the foramen magnum to the dorsal margin of the hard palate, any measurable degree of basilar impression becomes apparent." He observed that "all parts of the atlas and axis lie caudad of the 'base line'" for normal subjects. Patients with basilar impression exhibited a "displacement of the odontoid process of

the axis and most of the atlas to a level cephalad of the indicated base line" as well as a "cephalic bulge at the clivus."

List (1941) expresses his views on basilar impression as follows:

The described anomalies per se have little pathologic significance and, as a rule, produce no clinical symptoms. In a number of cases, however, malformations of the craniovertebral boundary eventually lead to dislocation of the bony structures and thus to encroachment on the neural canal. If, for instance, the basiocciput is underdeveloped or too soft, the thin bone surrounding the foramen magnum is mushroomed into the posterior cranial fossa by counterpressure of the unyielding cervical portion of the spine exerted against the weight of the skull in the upright posture.

In this condition, the basiocciput (i.e. the distal portion of the clivus and the lateral rim of the foramen magnum) becomes markedly thinned, often like paper, and bulges into the posterior cranial cavity. This protrusion may reach the plane of the posterior clinoid processes, the basal angle (the angle subtended from the tip of dorsum sellae to the nosofrontal suture and the tip of dorsum sellae to the anterior rim of the foramen magnum in the mid-sagittal plane) being thus increased from a normal 115 to 140 degrees to 180 degrees or more. Because of the resultant flattening of the base of the skull, the minor grades of basilar impression have been also termed "platybasia."

The foramen magnum is considerably narrowed by the bony protrusion. The atlas, which may be hypoplastic or malformed, lies in close approximation to, or is actually fused with, the occipital bone. Its superior articular facets usually are malformed or have undergone secondary arthritic changes. The intracranial invagination of the cervical portion of the spine brings the odontoid process into or above the level of the foramen magnum, which is thereby further narrowed. In some cases the dens was dislocated forward, beneath the clivus, producing extreme hyperextension (lordosis) of the entire cervical portion of the spine.

The real cause of basilar impression is unknown, but probably congenital maldevelopment or hypoplasia of the basiocciput accounts for the condition in most cases. Postnatal diseases, such as rickets, osteitis deformans, osteomalacia and hydrocephalus have been incriminated as etiologic factors in some instances, without much proof.

List describes the neurologic syndrome associated with basilar

impression:

In this condition the ventral surface of the pons and medulla oblongata is flattened or indented by the bulging invagination of the basiocciput. The ascent of the cervical portion of the spine through the foramen magnum further encroaches on the medulla. Since the tentorium

is practically rigid, the reduced space of the posterior fossa causes general compression of the cerebellum as well.

The neurologic picture, therefore, consists of bulbar and cerebellar signs. There are palsies of the lower (ninth to twelfth) cranial nerves and usually involvement of the ventrally situated pyramidal tracts. Cerebellar signs are due partly to direct compression and partly to foraminal obstruction. If the bony deformity is more marked on one side, an ipsilateral lesion of cranial nerves is combined with ipsilateral or contralateral signs of involvement of the pyramidal tracts. In some instances pressure on the anterolateral tracts led to dissociated sensory disturbances of syringomyelic type.

The considerable narrowing of the foramen magnum obstructs the ventricular and subarachnoid outlets at the foraminal level, resulting in internal hydrocephalus. Beginning foraminal obstruction may be clinically suspected when headaches and dizziness occur, especially on change of posture or on exertion. In advanced lesions all signs of a neoplasm in the posterior fossa may be present. As in other instances of long-standing hydrocephalus, secondary hypothalamo-hypophyseal signs, such as adiposogenital dystrophy and polyuria, have been observed.

List emphasizes the role of proper radiographic techniques in the evaluation of craniovertebral abnormalities, basilar impression in particular:

Roentgenographic examination establishes a definite diagnosis of the bony deformity. Owing to the shortness and immobility of the neck, however, it is often difficult to obtain satisfactory roentgenograms; for instance, it may be impossible to obtain a good anteroposterior projection of the upper cervical portion of the spine through the open mouth, since the atlas and axis are displaced upward. The best diagnostic information is secured from lateral views of the cervical part of the spine, from sagittal frontosuboccipital, or, better still suboccipitofrontal, projections (Chamberlain) of the skull and from the vertical submentobregmatic projection. Sometimes roentgenograms of the petrous bones in Stenvers' projection demonstrate well the odontoid process. These roentgenograms show the size and shape of the foramen magnum and its relation to the atlas and axis.

The diagnosis of basilar impression (platybasia) is easily made from the characteristic roentgenographic findings. In the neurologic picture bulbar involvement is striking. Mild forms of platybasia can be recognized in lateral roentgenograms of the skull, by drawing a line from the posterior tip of the hard palate to the dorsal aspect of the posterior rim of the foramen magnum. In the normal skull this line touches the posterior end of the clivus; but in a case of platybasia, the latter structure is elevated well above this line (Chamberlain).

Peyton and Peterson (1942) evaluate basilar impression in regards to its morphology, relationships to atlanto-occipital fusion and its potential for extensive neurological deficits:

BASILAR IMPRESSION, platybasia, and basilar invagination are terms used to designate a deformity of the bony structures about the foramen magnum. The basilar, condylar, and that part of the squamous portion of the occipital bone which surrounds the posterior part of the foramen magnum are displaced cranialward; the foramen magnum is irregular in outline instead of the usual oval shape; and most often it is smaller than normal, with its margins directed upward into the cranium. The downward tilt or angle of the clivus with the horizontal plane is decreased; it is broad and flat, and the petrous portion of the temporal bone is pushed upward. The floor of the posterior fossa is thin. There is a variable degree of fusion of the atlas with the occipital bone.

There has been much discussion in the literature concerning the etiology of basilar impression. Rokintansky believed that hydrocephalus was the cause, but although an associated hydrocephalus is found at times, the relationship is not clear. It is more probable that basilar impression is the cause and not the effect of the hydrocephalus. Trauma, rickets, and Paget's osteitis have been given as the cause in some of the case reports.... The evidence in favor of a congenital maldevelopment is so convincing that it is here assumed that basilar impression is a congenital anomaly, although it is possible that deformities simulating basilar impression may occur from other processes.

There are many varieties of anomalous development about the base of the occipital bone and the upper cervical spine, of which basilar impression is one of the more extensive. The other lesser anomalies may occur alone or in combination with basilar impression. These consist of defects in the posterior arch of the atlas, absence or fusions of cervical vertebrae (Klippel-Feil's syndrome), assimilation of the atlas, and "manifestations of an occipital vertebra."

All reports of basilar impression reviewed, in which the specimen has been dissected and described, indicate that assimilation of the atlas is a constant part of basilar impression, being found in every instance where the atlanto-occipital joint was examined.... It is also significant that in some specimens reported as assimilation of the atlas there is a deformity in the shape and size of the foramen magnum, and even in "manifestation of an occipital vertebra" similar changes occur. This would suggest that all these conditions are related and that basilar impression is an extreme grade of a group of anomalies which may occur about the upper cervical vertebra and base of the occipital bone.

Neurological symptoms may or may not be present in basilar impression. As a rule, they do not appear until after adolescence, but they are

progressive, and the lesion is frequently fatal.... Neurological signs are irritation and paralysis of cervical nerves and spinal cord tracts due to compression at or near the foramen magnum; irritation and paralysis of cranial nerves in the posterior fossa; compression of the medulla oblongata by the odontoid process, which projects through the foramen magnum into the posterior cranial fossa; cerebellar disturbances due to compression of the cerebellum in a shallow posterior cranial fossa; finally, an increase in intracranial pressure.

Peyton and Peterson also discuss the radiographic considerations of basilar impression:

A lateral view of the cervical spine including the base of the skull will give sufficient information to make a diagnosis of basilar impression. We make this statement, because we believe that all cases will have some degree of assimilation of the atlas in which the posterior arch will be fused with the occipital bone. Consequently, in a lateral roentgenogram of the upper cervical spine, there will either appear a very rudimentary posterior arch or none at all will be visible. In addition, a lateral view will demonstrate the high position of the odontoid process. Chamberlain advocates drawing a line from the posterior edge of the hard palate to the posterior lip of the foramen magnum. If the odontoid process projects above this line, basilar impression may be suspected. We have observed this in our cases but find it very difficult to be certain of the above-mentioned landmarks on the roentgenograms. Elevation of the floor of the posterior fossa around the foramen magnum is not an outstanding roentgenographic finding. Changes in the basal angle are inconstant.... Elevation and rotation of the medial ends of the petrous pyramids is also an inconspicuous roentgen finding, if present at all. A decrease in size and distortion of the shape of the foramen magnum are of constant occurrence, but seem to be extremely difficult to record conclusively on the films.... We have found it possible, however, to demonstrate quite well a synostosis at the atlanto-occipital joint.

Hadley (1948) briefly discusses basilar impression as a secondary or an acquired disorder. He views this condition as follows: "Basilar impression, an acquired distortion secondary to softening of the base of the skull, causes development of pressure within the cerebellar fossa by invagination of that part."

There are two principal types of congenital anomaly: atlanto-occipital fusion....and the manifestation of occipital vertebra.... To these must be added those cases of acquired basilar impression or invagination secondary to softening of the skull base from osteitis deformans, osteogenesis imperfecta, osteomalacia, rickets, and also, as mentioned by one author, lipoidosis, senile osteoporosis, osteop-sathyrosis congenita and cleidocranial dysostosis.

In the acquired cases secondary to a softening of the base of the skull, the invagination of the occiput upward into the posterior fossa acts as a piston. The tentorium being fixed, pressure is exerted upon the cerebellum. Brain substance may be forced to herniate downward into the spinal canal somewhat, as noted in the Arnold-Chiari syndrome. In these secondary cases as the skull base widens, there may be traction upon the posterior five or six pairs of cranial nerves.... In addition to the increased intracranial pressure and hydrocephalus, the neurological symptoms are those of irritability or paralysis involving the cranial or cervical nerves and the spinal cord tracts.

In regards to congenital cases of atlanto-occipital fusion, Hadley remarks, "basilar invagination may be minimal or entirely lacking and the symptoms may result largely from deformity of the foramen magnum."

McGregor (1948) discusses and summarizes the etiologic basis of basilar impression:

The earliest authors...had recognised that more than one pathological state might be responsible for the deformity of basilar impression, but it has only fairly recently been appreciated that the vast majority of cases appear to fall within the realm of congenital defects of development and are not necessarily preceded by any bone disease in its generally accepted meaning. This group of cases, frequently found occurring together with other developmental bony and neurological defects, has been well termed "primary basilar impression." The small group of cases occurring clearly as the result of bony disease of the skull, thinning, osteoporosis, etc., or in association with some other generalised developmental anomaly, such as osteogenesis imperfecta, is referred to as "secondary basilar impression."

McGregor proposed the following classification for the etiology of basilar impression:

#### THE CAUSES OF BASILAR IMPRESSION

1. Primary Basilar Impression  
A congenital anomaly of development in the cervico-occipital region.
2. Secondary Basilar Impression
  - (a) Involvement of cranial bones in generalised osteoporotic conditions.
    - (i) Osteomalacia, rickets, senile atrophy.
    - (ii) Paget's disease (osteitis deformans).
    - (iii) Renal rickets and hyperparathyroidism.
  - (b) Delayed or defective ossification of cranial bones.
    - (i) Osteogenesis imperfecta.

- (ii) Chondro-osteo-dystrophy.
- (iii) Cretinism.
- (iv) Cranio-cleido-dysostosis.
- (c) Local bone destruction by tumour or infection. (no reported cases)
- (d) Thinning of the cranial bones due to chronic hydrocephalus. (in doubt)
- (e) Trauma. (uncertain)
  - (i) Sudden - violent.
  - (ii) Prolonged - mild. Carrying heavy burdens on head, etc.

In reference to neurological manifestations of basilar impression,

McGregor writes:

The presenting symptoms may be predominantly those of raised intracranial pressure and hydrocephalus, following on disturbances of the cerebro-spinal fluid circulation; symptoms of cerebellar involvement due to encroachment on the posterior fossa; symptoms of bulbar compression, cranial nerve involvement, etc.; symptoms of constriction of the cord in the region of the first cervical segment, following on stenosis of the foramen magnum, or atlanto-axial dislocation; or symptoms of degenerative changes in lower cervical segments.

These latter changes are attributed to various pathological processes, such as associated spinal dysraphism, the development of obstructive hydromyelia, and the development of anoxic degenerative changes, following an interference with the spinal arteries and veins in the region of the foramen magnum.

It will be seen that a great variety of symptom complexes may be produced, and the condition may be mistaken for tumour of the posterior fossa, syringomyelia, motor neurone disease (chronic bulbar palsy and amyotrophic lateral sclerosis), transverse myelitis, spinal cord tumour, spastic paraplegia, or disseminated sclerosis.

The purpose of McGregor's paper was "to contribute one more step in the development of radiological criteria for diagnosis" of basilar impression. On 203 randomly selected true lateral radiographs of normal African Bantu Negro skulls from the files of the Department of Radiology of the Johannesburg Non-European Hospital, he statistically analyzed the relationship of the odontoid process to a modification of Chamberlain's reference line.

The base line was carefully drawn from the upper surface of the posterior edge of the hard palate to the most caudal point of the outer surface of the occipital bone. The tip of the odontoid process was defined and its shortest distance from this line was measured. When the tip of the dens coincided exactly with the line, the figure 0 was

recorded; when it fell below the line, a "plus" quantity was recorded; and when above the line, a "minus" quantity.

His calculations were performed on male and female data separately, but the difference was so small as to consider the male and female observations as one population. The mean distance of the tip of the odontoid process from McGregor's base line was +1.32 mm.; that is to say, the tip of the odontoid process was found to be 1.32 mm. below the base line on the average. The standard deviation was 2.62 mm. with a range of +8 mm. to a -7 mm. He concluded: "When the tip of the odontoid lies a distance of 4.5 mm. above the base line, the measurement lies on the extreme edge of normality, and pathology must be seriously considered."

McGregor compared his results with those from a similar investigation performed by Saunders, who measured the shortest distance of the tip of the odontoid from Chamberlain's line in 100 normal lateral radiographs (presumably of European skulls). "He (Saunders) found the arithmetical mean position of the odontoid to be 1 mm. below the base line (Chamberlain's), with a standard deviation of 3.6 mm." McGregor, therefore, makes the following statement based on these studies: "The close similarity....between these results and those of Saunders makes it probable that the figure 4.5 mm. may be taken as the outer limit of normality for both African and European races."

McGregor advocates the use of his "base line" instead of Chamberlain's reference line. He states his "base line" has two advantages:

Anyone, who has endeavoured to apply Chamberlain's line to a large number of lateral radiographs of the skull, will agree that the posterior edge of the foramen magnum cannot always be defined with certainty. In many cases tomography will define this point, but a few cases have been encountered where, for one reason or another, even mid-sagittal tomograms (planigrams) will not show up the posterior lip of the foramen magnum.

The most caudal point of the occipital curve approximates closely the posterior lip of the foramen magnum in the normal skull, but has this advantage: that as invagination of the foramen takes place in basilar

impression, it will not move cranially as much as would the posterior lip of the foramen. The base line, therefore, by this new definition, remains relatively more static in advancing basilar impression than does Chamberlain's original line, thus demonstrating to greater advantage the ascent of the odontoid process.

McGregor critiques other measurements and indices used in the determination of basilar impression. These include the foramen magnum-clivus angle of Boogaard, Boogaard's line, and Weisbach's facial angle. He states that the foramen magnum-clivus angle of Boogaard and Boogaard's line, "though not used, are still perfectly valid indices of basilar impression."

The foramen magnum-clivus angle....is the angle subtended by the antero-posterior diameter of the foramen magnum with the plane of the clivus. Its normal variation is, according to Boogaard,  $119\frac{1}{2}$ - $136$  degrees, and its enlargement beyond this limit is characteristic of basilar impression.

The line drawn from the nasion to the "lower surface of the part lying behind the foramen magnum,"....we will call Boogaard's line. He found that first the anterior and then the posterior edge of the foramen magnum rises above this line with advancing impression of the base.

Another angle, which we need only mention in passing, is the facial angle of Weisbach, which is defined as "the angle at the chin, formed by a line drawn from the nasion to the central point at the antero-inferior margin of the mandible, and another from this point to the anterior margin of the foramen magnum." Though this angle undoubtedly becomes reduced with upward dislocation of the foramen magnum, it probably varies with racial type; it may be reduced in acromegaly and cretinism and appears to be an unnecessarily indirect method of estimating the deformity in question.

McGregor discusses the validity or invalidity of the measurement now referred to as the basal angle (of Boogaard).

Boogaard, from his study, found that the angle between the plane of the clivus and the plane of the sphenoid became increased in some cases of basilar impression.... It may be accurately measured on the lateral X-ray of the skull by drawing a line from the nasion to the centre of the pituitary fossa and another from this point to the anterior lip of the foramen magnum. Some authors prefer to measure the angle subtended at the tuberculum sellae rather than that subtended at the centre of the sella turcica.... There is a variation of not more than two or three degrees between the two methods of measuring the angle.

The same 203 lateral radiographs (normal African Bantu skulls) were taken, and the basal angle was measured. In none was the basal angle

greater than  $147^{\circ}$  or less than  $120^{\circ}$ . The mean was found to be  $134^{\circ}$  with a standard deviation of  $6.44^{\circ}$ .... Brailsford gives the normal range as  $135^{\circ} \pm 10$  per cent (normal European skulls).... We may conclude that there is unlikely to be much variation of the basal angle with racial type, so far as Africans and Europeans are concerned.... Angles greater than  $148^{\circ}$  may consequently be looked on as highly suggestive of abnormality.

An attempt was made to determine whether any relationship exists in the normal skull between the basal angle and the distance from the tip of the odontoid to base line. A graph was therefore constructed in which the distance of the tip of the odontoid process from the base line was plotted against the basal angle.... The result indicates that no significant relationship exists between this measurement and the basal angle in the normal Bantu skull. In view of the fact that the odontoid-base line distance is generally accepted as a most useful index of basilar impression, the absence of any relationship between it and the basal angle in the normal skull is important.

Walsh was the first author since Boogaard to draw attention to the fact that the basal angle was indeed a bad and inconstant index of basilar impression, and that though the basal angle is usually increased with impression of the base, the latter pathology may exist without any increase in the basal angle.... The basal angle is indeed not a measurement of the degree of impression of the base, but is an index of the position of one part of the base relative to another.

McGregor disagrees with the synonymous use of the terms "basilar impression" and "platybasia," but prefers that the term "platybasia" should be reserved for those cases with an increased basal angle. "The name 'platybasia' should be reserved....to designate flattening of the base of the skull." "As the (basal) angle increases towards  $180^{\circ}$  they may be seen to have truly a flattened base."

McRae (1953), in his treatise regarding correlation of anatomical and neurological findings of bony abnormalities of the foramen magnum region, reports his experiences with 21 cases of pure platybasia and basilar impression:

Platybasia means flattening of the base of the skull, that is, a basal angle that approaches 180 degrees. The basal angle is the angle formed by the intersection of the plane of the clivus and the plane of the anterior fossa.... I have decided to use lines from the tuberculum sellae to the nasofrontal suture and to the anterior margin of the foramen magnum to subtend the basal angle.

Basilar invagination or impression means an upward bulging of the margins of the foramen magnum. It may be a congenital abnormality or secondary to softening of the bone about the foramen magnum. Since the occipital condyles bear the thrust of the spine, they must be the first parts of the base to be displaced. If the tips of the condyles are seen at or above the foramen magnum line, basilar invagination must be present. The condyles are close to the anterior lip of the foramen magnum, and presumably the anterior lip should rise to a greater degree than the posterior lip. This alteration in the plane of the foramen magnum is best shown by Boogaard's angle, the angle subtended by the plane of the clivus and the plane of the foramen magnum as seen in lateral projection. The range of the normal is from 119 degrees to 136 degrees. As the base invaginates, this angle increases. The upward curvature of the lateral edges of the foramen magnum may be seen in true lateral films of the skull and is another sign of basilar invagination. The tip of the odontoid process of the axis is above Chamberlain's line in about one-third of normal individuals. If the tip is more than 3 mm. above Chamberlain's line, basilar invagination is almost surely present. McGregor's base line (from hard palate to the lowermost surface of the occipital squama) is easier to draw and probably more significant than Chamberlain's line.

It is important to realize that platybasia and basilar invagination are uncommon in association with assimilation of the atlas. Even when present, they are slight and unimportant. Four of the twenty-eight patients (with assimilation of the atlas) had basal angles of 145 degrees, and only two of these had neurologic signs. Three of the twenty-eight had basal angles of 150 degrees, and only one had neurologic signs. Seven of the twenty-eight had slight to moderate basilar invagination. Of these, three had no neurologic signs, and four had neurologic signs. Seventeen had neither platybasia nor basilar invagination.

A common finding was a convex clivus. It was found in twelve patients (of 21 patients with basilar invagination and/or platybasia) in contrast to only four patients (out of 28 patients) in the group with assimilation of the atlas. The four patients who had assimilation of the atlas and a convex clivus all had slight basilar invagination or platybasia. There was often a hump at the sphenoccipital synchondrosis associated with a short basioccipital, suggesting that this deformity was present before closure of the synchondrosis. Possibly early closure of this synchondrosis or hypoplasia of the basioccipital played a part in producing the platybasia.

The anterior arch of the atlas could be seen well below the anterior lip of the foramen magnum in sixteen cases, in contrast to assimilation of the atlas, where the anterior arch was usually close to the basiocciput. The posterior arch was usually close to, or touching, the posterior margin of the foramen magnum and, in two cases, seemed to be inside the foramen magnum.

In all of the cases of platybasia and basilar invagination, the dens was normal in shape and did not bend backwards more than 20 degrees.

In assimilation of the atlas, the dens was often abnormal in shape and direction.

Eight patients with platybasia and/or basilar invagination had neurologic signs that were considered to be due to the lesion. The signs were less severe and less constant than in occipitalization of the atlas. It is worth noting that two of these patients had bulbar signs and two showed Horner's syndrome.

McRae and Barnum (1953), in a discussion of occipitalization of the atlas, make references to platybasia and basilar impression. Their article analyzes 25 cases of occipitalization of the atlas.

The basal angle was usually normal.... We feel that the upper limit of normal is  $140^{\circ}$  and use the word platybasia to denote a basal angle of  $145^{\circ}$  or more. Twenty-one cases had no platybasia, the basal angles varying from  $120^{\circ}$  to  $140^{\circ}$ . Two symptomless cases had basal angles of  $145^{\circ}$  and  $150^{\circ}$ , and 2 cases with symptoms had basal angles of  $145^{\circ}$ . This surprised us as we used to believe that platybasia frequently accompanied occipitalization of the atlas and played a part in the production of symptoms. Apparently it does not. We assumed that platybasia and assimilation were found together, because, in many of the cases of platybasia, the atlas was in contact with the occipital and seemed assimilated. Critical review of the operative and autopsy findings, as well as laminagraphic and bending film examinations, has forced us to revise our ideas. Anteroposterior laminagrams or lateral laminagrams in flexion and extension will show atlanto-occipital joint spaces or atlanto-occipital movement in nearly all cases of platybasia.

If the line of the occipital squama is convex upward, or if it lies above the line of the foramen magnum, or if the occipital condyles lie on or above the line of the foramen magnum, we say that basilar impression is present. Ten cases had no basilar impression. Fifteen cases had slight impression. The patient with the basal angle of  $150^{\circ}$  had no basilar impression, as did one of those with an angle  $145^{\circ}$ . Seven of those without basilar invagination had neurological signs. It is safe to say that the slight platybasia and the slight basilar impression, that is present in some cases of assimilation of the atlas, have nothing to do with the production of neurological signs.

In basilar invagination the petrous tips are elevated. In normal persons the petrous ridge in standard anteroposterior or postero-anterior projections sloped slightly downward as one follows it medially from the tegmen tympani or arcuate eminence. In only 4 cases of assimilation were the tips above the horizontal and then very little.

In normal skulls the clivus is usually concave posteriorly as shown by the mid-sagittal laminagram. The clivus is the posterior surface of the basi-occiput and basisphenoid and does not extend onto the dorsum

sellae. In basilar invagination the clivus is usually convex posteriorly. In these cases of assimilation of the atlas, the clivus was convex posteriorly in only 4 cases.

Bull, Nixon, and Pratt (1955), in a very statistically oriented paper, attempted to compare three different measurements in radiographic diagnosis of basilar impression. In addition to the relationships of the tip of the odontoid process to Chamberlain's and McGregor's base lines, Bull et al. introduce an angular measurement as another criterion for basilar impression.

In cases of basilar impression secondary to bone softening, it is the weight-bearing parts of the occipital bone, namely, the antero-lateral parts adjacent to the foramen magnum, which rise. Since the condylar portions of the atlas rise pari passu with the occipital condyles, it was suggested that the angle between the plane of the hard palate and the plane of the atlas vertebra would measure the degree of basilar impression. The plane of the atlas is obtained by drawing a line from the middle of the anterior arch of that vertebra to the middle of the posterior arch. Although this angle might be expected to vary with the degree of flexion or extension of the neck, we have not found this to be the case.

Lateral radiographs of the radiographically normal skulls of 120 patients of the National Hospital were chosen for measurement, each decade between the ages 10 and 69 years being represented by 10 males and 10 females. From each radiograph were determined the values of Chamberlain's measurement c in mm. and McGregor's measurement m in mm. (that is, the perpendicular distances between the odontoid tip and the respective base lines), and the angle in degrees between the plane of the hard palate and the plane of the atlas vertebra, henceforth referred to as the angle B.

Certain other measurements were made which failed to discriminate between normals and abnormals, and which are therefore not recorded: these comprised the length of the clivus, the relationship to the plane of the hard palate of the anterior and posterior margins of the foramen magnum, and the angle between the plane of the hard palate and the plane of the clivus. The basal angle x in degrees was also measured and...was found to give a limited discrimination between certain of the groups studied.

Bull et al. establish normal values of the above measurements for these 120 "normal" subjects as follows:

	<u>Mean</u>	<u>SD</u>
Chamberlain's measurement <u>c</u>	-2.86 mm.	3.03 mm.
McGregor's measurement <u>m</u>	-0.39 mm.	3.02 mm.
Bull's angle <u>B</u>	0.58°	4.04°
Basal angle <u>x</u>	130.23°	5.38°

The values of c and m are considered positive if the odontoid tip is above the respective base lines.

Bull et al. selected twenty subjects with the provisional diagnosis of basilar impression and compared them with their normal set of values:

For the group of patients judged provisionally to have primary basilar impression, there were chosen those patients of the National Hospital in whom a clinical or radiographical diagnosis of primary basilar impression had been made, and whose measurements for at least one of the three criteria were above the appropriate mean value for the 120 normal subjects by three or more times the corresponding standard deviation; namely, B = +13° or more; c = +7 mm. or more; and m = +9 mm. or more. 20 such patients were found: of these, 18 were abnormal according to the angle B (the 2 patients not so abnormal had, nevertheless, values of +10° and +11° respectively), 12 were abnormal according to the Chamberlain criterion, and 12 according to the McGregor criterion. 9 patients were abnormal according to all three criteria, and 6 abnormal according to the angle B alone.

These 20 radiographically abnormal patients could be divided clinically into three groups: the first (10 patients) in which the radiological abnormality was an incidental finding, not associated with any symptoms; the second (7 patients) in which a clinical diagnosis of syringomyelia had been made; and the third (3 patients) in which the neurological symptoms and signs could be explained by a local lesion at the level of the foramen magnum.... The 10 symptom-free patients were found in a series of about 30,000, giving a figure of general prevalence of the abnormality of at least 1 in 3,000.

To establish a possible mode of inheritance, Bull et al. had all available relatives of the 20 abnormal patients examined radiographically and came to the following conclusions:

The 39 relatives were found to fall into two clearly distinct groups on the basis of the angle B alone: 28 of them having values of B distributed more or less symmetrically about the estimated general mean with the same standard deviation; and the remaining 11 forming a separate group with a mean value of about +16° and a standard

deviation of about  $4^{\circ}$ , the high positive value indicating the presence of the malformation. It is therefore concluded that there is a real (genetically determined) skeletal malformation, detectable principally by means of the angle B and not nearly so well by the other two measures proposed, as distinct from a mere statistical abnormality. That the angle B is the best diagnostic criterion is supported by the fact that it played the principal role even in the provisional statistical definition of abnormality (it failed--but only just--to define 2 only of the 20 statistically abnormal patients; whereas Chamberlain's and McGregor's measures each failed in 8 cases, with values as low as +1 mm. and +3 mm. respectively).

It is concluded that primary basilar impression is a genetically determined skeletal abnormality, which is best discriminated by means of the angle between the plane of the hard palate and the plane of the atlas vertebra.... Although there are too few patients to enable a firm conclusion to be drawn, the findings are compatible with the tentative hypothesis that the mode of inheritance is Mendelian dominance with an occasional failure of manifestation of the abnormal gene.

Spillane, Pallis, and Jones (1957) express their views of basilar impression and offer analysis and criticism of the various diagnostic criteria used to define basilar impression:

Platybasia denotes an increase in the breadth (obtuseness) of the basal angle of the skull, which is the angle made by the intersection of the plane of the sphenoid with the plane of the clivus. Basilar impression is a deformity of the base of the skull consisting in an elevation into the cranial cavity of a variable part of the bony rim of the foramen magnum.... The terms platybasia and basilar impression, synonyms by implication in the title of Chamberlain's important paper, do not refer to the same anomaly. Invagination of the rim of the foramen magnum is not always associated with an increase in the basal angle of the skull; in fact, in the majority of cases of basilar impression, there is no platybasia.

Congenital bony defects at the cranio-vertebral junction may be harmless and unassociated with symptoms and signs.... In several cases multiple anomalies were present, a finding which does not support the suggestion sometimes made that, whereas isolated basilar impression may be asymptomatic, its presence in conjunction with other skeletal defects is always associated with neurological signs.

Isolated basilar impression is usually asymptomatic; a syringomyelic syndrome is the commonest clinical concomitant.... When this (compression of the neuraxis at the level of the foramen magnum) arises, basilar impression is rarely the sole anomaly. There is usually occipitalization of the atlas or marked atlanto-axial dislocation, which narrows the effective antero-posterior diameter of the foramen magnum. Myelography demonstrates the obstruction.... It is doubtful whether platybasia is of any clinical significance.

Spillane et al. refute the validity and reliability of such indices as the basal angle, Chamberlain's line, McGregor's line, Boogard's angle, and Bull's angle to determine basilar impression. They claim that "Antero-posterior tomography of the foramen magnum is the only certain way of diagnosing basilar impression." Their comments on this matter are as follows:

No correlation could be established between the basal angle and such presumed indices of basilar impression as the relation of the tip of the odontoid to Chamberlain's line, McGregor's line or the "digastric" line. Nor was there any correlation between the basal angle and Bull's angle, Boogard's angle and the diagnostic "tracings" obtained from the antero-posterior tomograms.

The vast majority of patients with basilar impression, occipitalization of the atlas, atlanto-axial dislocation and malformations of the foramen magnum and upper cervical spine have a normal basal angle. This angle is, therefore, of little use in the diagnosis of cranio-vertebral anomalies.

Two minor drawbacks to the use of Chamberlain's line are (a) that the posterior lip of the foramen magnum, one of the points of reference, is often difficult to define in the average lateral radiograph; and (b) that, in certain types of basilar impression, the posterior lip of the foramen magnum is itself invaginated. It is obviously a disadvantage in assessing such an abnormality to have a point of reference that may itself be mobile.

Both Chamberlain's line and McGregor's line are drawn from the posterior edge of the hard palate. This point is easy to define and conveniently situated, but it is not part of the base of the skull. Now basilar impression, by definition, is an abnormality in which parts of base (the rim of the foramen magnum and occasionally the adjacent area) are displaced in relation to the remainder of the base. The posterior edge of the hard palate is not a suitable landmark to use when defining these altered relationships. Its position is variable and its relation to the base inconstant, depending on the development of the facial bones. It can readily be shown that the distance between dorsum sellae and the hard palate may vary considerably (1.7 cm. in their radiographic study of 30 normal adult skulls).

In 1941 Lindgren pointed out that impression could be confined to the parasagittal "weight-bearing" part of the rim of the foramen magnum and that it was certainly present, when "a displacement of the region around the foramen magnum has reached such a degree as to be discernible on a frontal picture".... Lindgren's observation, amply confirmed, has stimulated attempts to establish the diagnosis of basilar impression from antero-posterior radiographs and tomograms. In addition to being of value in demonstrating elevation of the parasagittal

condylar region, the antero-posterior films also have the advantage over lateral radiographs that they permit base lines to be drawn between points directly related to the floor of the posterior fossa.

Fischgold and Metzger (1952) pointed out that in the antero-posterior film of the skull (or better still in the transoral projection) a line joining the lower extremities of the mastoid processes passed through the atlanto-occipital articulations and that the tip of the odontoid was often situated on the same line. In cases of basilar impression, one or both atlanto-occipital articulations are elevated above this base-line. In view of the variability in the size of the mastoid processes, the authors later proposed a more constant base-line, drawn between the two digastric grooves (each groove is situated at the junction of the medial aspect of the mastoid process with the base of the skull).... In the experience of those familiar with the technique, the digastric line usually passes well above the odontoid and occipital condyles.

Antero-posterior tomograms of the base of the skull are of the greatest value in diagnosis of basilar impression. Only such films enable one to identify the actual rims of the foramen magnum. Serial tomographic cuts will outline the elevation of the rims and show the upward sweep of the floor of the posterior fossa towards the foramen magnum.

We feel that Chamberlain's line, McGregor's line, Fischgold's line and the "digastric line" are useful in assessing the position of the odontoid, a high-lying odontoid being common in basilar impression, but occurring also from other causes. Increases in Boogard's angle (defined by the intersection of the plane of the clivus with the plane of the foramen magnum, normal range: 119.5 - 136 degrees) denote either a true impression or increase in the slope of the foramen magnum. Bull's angle (determined by the plane of the hard palate and the plane of the atlas vertebra) may exceed 13 degrees in true basilar impression, but also in patients with an abnormal slope of the foramen and in certain patients with a marked cervical lordosis.

Epstein (1962), in his radiologic text of the spine, discusses briefly basilar invagination, basilar impression and platybasia. He contends that these terms should not be used interchangeably. "Platybasia indicates a flat, broad, wide base and is used correctly by anthropologists for classifying cranial types." Platybasia is present when the basal angle approaches 180 degrees. Basilar invagination, however, refers to "an indentation of the upper cervical segments into the base of the skull, as if the weight of the cranium causes a sagging of its base against the rigid cervical spine." He further states:

Simultaneously, and to more variable extent, the tips of the petrous pyramids become directed upwards. The malformation is associated with osteomalacia, rickets, osteogenesis imperfecta, cleidocranial dysostosis, hyperparathyroidism, the lipoidoses, and quite frequently with Paget's disease.

Deformity of the margins of the foramen magnum and the base of the skull frequently accompanies bony abnormalities of the craniovertebral junction. The foramen magnum becomes misshapen and encroached upon because of assimilation of the atlas or the presence of transitional vertebrae. Because of this, the tip of the dens projects into the cervical spinal canal just below and at the foramen magnum, thereby narrowing the space available for the medulla oblongata and the proximal cervical spinal cord.

Basilar impression or invagination exists without specific symptoms in a rather large proportion of cases. However, when the dens projects sufficiently into the cervical spinal canal, when there is undue mobility of this structure, or when the foramen magnum is sufficiently encroached upon, neurologic changes result either from direct pressure, vascular compression on the adjacent structures or from interference with the cerebrospinal fluid circulation. This may take place regardless of the anatomic cause, and gives rise to perplexing problems simulating syringomyelia, multiple sclerosis or other degenerative demyelinating diseases, as well as pictures mimicking tumors of the posterior cranial fossa or upper cervical spinal canal. Pressure against the cranial nerves or upper cervical nerves may produce paralysis or symptoms referable to cerebellar or medullary compression.

McRae (1969) concurs with Spillane et al. concerning the value of tomography to diagnose basilar invagination and the inadequacy of the various linear measurements.

Basilar invagination, or basilar impression, means invagination of the margins of the foramen magnum upward into the skull. It is difficult to measure objectively. Various lines have been described which supposedly diagnose or exclude basilar invagination, but none of them is entirely satisfactory because of variations in the length of the clivus and in the size of the occipital condyles. For example, in about 25 per cent of normal individuals, the tip of the odontoid process is above Chamberlain's line. Antero-posterior and lateral tomograms of the foramen magnum offer the best means of showing actual upward displacement of the margins of the foramen magnum, the absolute criterion for the diagnosis of basilar invagination.

Platybasia, a term used mainly by anthropologists and anatomists, signifies that the basal angle of the skull is abnormally great. It is not synonymous with basilar invagination, although the two often coexist.... It is generally considered that the skull is platybasic, if the basal angle is greater than 142 to 144 degrees.... Since the

floor of the anterior fossa of the skull has three different levels, and since the clivus is sometimes curved, as seen in the lateral view, it is difficult to draw the basal angle on lateral skull radiographs.

When there is marked basilar invagination, the atlas may be surrounded by the occipital bone, and it may be difficult to diagnose or exclude occipitalization of the atlas, except with laminagrams. In basilar invagination, the odontoid process is usually not within the foramen magnum. In this lesion, pressure on the upper cervical cord seems to come from all sides. Usually the cerebellar tonsils are below the foramen magnum. This low position of the tonsils should not be called Arnold-Chiari malformation, since, in basilar invagination, the cervical nerve roots usually pass downward to reach the intervertebral foramina in normal fashion.

McRae (1971), in a radiology text of the skull, reiterates many comments of his previously cited article (1969), but in some respects in more detail. Some statements do not need to be repeated; however, certain items, particularly in regard to measurements, are worth summarizing.

Certain measurements about the craniovertebral junction are of medical importance (McGregor, 1948; Fischgold et al., 1952). Chamberlain's line joins the posterior end of the hard palate to the posterior lip of the foramen magnum. McGregor's line joins the posterior end of the hard palate to the lowermost point of the occipital squama. The digastric line joins the right and left digastric notches, and the bimaistoid line joins the tips of the right and left mastoid processes. In about 50% of normal persons, the tip of the odontoid is at or below Chamberlain's and McGregor's lines. If more than half of the odontoid process is above one of these lines, basilar invagination is probably present. In normal patients the digastric line is 11 mm. ( $\pm$  4 mm.) above the middle of the atlanto-occipital joints. Basilar invagination is almost certainly present when the atlanto-occipital joint is at or above the digastric line. In addition to basilar invagination, some other conditions may cause the odontoid process to be high in relation to the lines of Chamberlain, McGregor, and Fischgold. These include occipitalization of the atlas, platybasia, a high atlas, a short clivus, or combinations of these.

The roentgenographic measurement of basilar invagination is difficult. Various lines and angles have been described that supposedly diagnose or exclude basilar invagination, but none is entirely satisfactory, because normal variations are seen in the length of the clivus, the size of the occipital condyles, and the plane of the foramen magnum. Anteroposterior and lateral tomograms of the foramen magnum offer the best means of showing actual upward displacement of the margins of the foramen. This displacement is the absolute criterion for the diagnosis of basilar invagination. Because of their practical usefulness, Chamberlain's line (1939), McGregor's line (1948), and the digastric line are still of value; but they must be used judiciously.

Regarding assimilation of the anterior arch of the first cervical vertebra and its relationship to the cited reference lines, McRae points out:

Since the second cervical vertebra is closer to the skull than normal, the odontoid process is above Chamberlain's line. The atlantoaxial joints then are usually at or slightly above the digastric line. True invagination of the foramen magnum, however, is often not present.

### Craniofacial and Other Skeletal Relationships

Throughout the literature dealing with skeletal abnormalities of craniovertebral junction, references to altered facial structure, head posture and other skeletal anomalies have been fostered, although in many instances in a casual manner or as an aside. Most authors report descriptive information of a specific or singular individual with associated facial anomalies and other skeletal defects. Statistical data in most instances is lacking.

Dwight (1904) describes cases of craniofacial alterations associated with such craniovertebral junctional abnormalities as assimilation of the atlas. He points out certain facial and cranial compensations that may occur.

The rotation (of fused occiput on the atlas), however, is very important, as it cannot but have an effect on the face. Of course, if the inferior articular surfaces of the atlas are placed on a horizontal plane, the side of the skull into which the arch of the atlas has been absorbed will be lower than the other, and the median line of the face will slant downwards to the opposite side, but this may be masked by a change in the position of the spine, or...by a compensatory twist in the face.

In describing another case, Dwight adds:

If we put the axis in approximately its normal position, the face is turned strongly to the right; but by a very remarkable manifestation of the law, there is a compensatory distortion of the bones, an effort, as it were, to diminish the false position by twisting itself to the left. A very striking feature is that the sockets of the teeth do not run perpendicularly to the alveolar processes, but slant obliquely to the left, bringing the line of their free edges more nearly horizontal than is that of the transverse axis of the atlas. Remembering that the atlas and skull are fused into one piece, this shows a twist occurring in the interstitial structure of the bone. In the same way the nose does not continue the direction of the sagittal suture to the right, but presents a distinct twist to the left. This vital effort to correct a deformity is a feature which apparently has been neglected in studies of obliquity of the face.

In discussing two cases of union of the atlas and occiput by a paramastoid process, Dwight further writes:

The reader will remember, that it was pointed out in cases of symmetrical fusion of half the atlas with the edge of the foramen magnum, that the transverse process of the side of the atlas which is free is

further forward in relation to the base of the skull. Here the same thing occurs on the side of the paramastoid process. The face is twisted on the skull very much to the left, with the left side higher. Then an effort has been made to correct this by a reverse twist in the lower part of the face, tending to bring the teeth into a horizontal line and to turn the lower part of the face back to the right. Thus, while the top of the nose turns to the left, the nasal spine points nearly straight forward.

(Second case) If we place the atlas transversely, the skull instead of pointing forward turns very strongly to the left, the left orbit being the higher; but the lower part of the face and especially the line of the teeth show the reverse twist, by which this is to some extent corrected.

The following quotations are taken from Dwight's lengthy discussion of facial obliquity in its relationship to craniovertebral anomalies:

Finally we come to the significance of obliquity of the face, and to how far it may be considered of diagnostic value as to the cause of its production. A very important point that has not been sufficiently grasped is that the obliquity cannot be adequately represented in a single plane.

The difference, both of the height of the (occipital) condyles and of the advancement of one before the other, naturally turns the face to the opposite side from the more advanced one. Moreover, in certain forms of anomalies the more advanced condyle is also the higher, so that the eye on the same side is higher than the other. Now comes into play a tendency of the organism to correct an unfortunate condition of affairs.... The result of all this is that, though the back of the head is turned to the right, the front part no longer points frankly to the left, but has so twisted itself as to look to the front. What has not occurred in the way just described has been aided by a twist of the spine, so that the eyes look forward.... The chin, which originally was higher on the right, has made itself remarkably symmetrical by a twist of the face around an antero-posterior axis. The right side of the face will be longer, fuller, and altogether larger than the left.

I am far from contending that this is what always occurs, because in nature the causal conditions are so bewilderingly complex that one cannot be sure just how the matter stands. While this chain of events can be plausibly demonstrated in some of the skulls with fused asymmetrical atlas, it may exist when there is nothing irregular in the joint.

Under ordinary circumstances the unevenness of the face is very slight; under other conditions it may be very great; and it is in these that the reverse compensatory twist is the most pronounced. Of course, many other factors must play an important and also an indefinable part in the moulding of the face.

Thus, variations which bring the condyles to a different level will have their effect on the face. Could we be sure that there were no other influences at work, we could draw a pretty close causal connection between certain anomalies and certain types of face and vice versa; but, as this is something that we never shall be sure of, we must exercise great caution in drawing conclusions.

Although not addressing craniofacial compensatory relationships specifically, Gladstone and Erichsen-Powell (1915) make the following observation:

Speaking generally, variation about a mean, with compensatory changes in other regions of the body, may be regarded as an established biological principle, which governs or acts on this region as well as on growth and development in general.

List (1941) presents case histories of seven patients with assorted anomalies of the craniovertebral junction (basilar impression, assimilation or fusion of the atlas to the occiput, other cervical fusions with dislocations, Arnold-Chiari deformity, and combinations thereof). It is of note that all seven have some form of head tilt, or rotation and cervical distortion and that four have some degree of facial asymmetry, one associated with marked mandibular overgrowth and prognathism, and another with a significant dental malocclusion.

List makes the following statements:

Since fusion of the atlas with the occiput may be unilateral, or at least more pronounced on one side, there may be secondary rotation and lateral tilting of the atlas with compensatory torsion and asymmetry of facial bones.

Asymmetric fusion of the atlas or of other cervical vertebrae may be suspected, if one observes torsion or lateral tilting of the head with asymmetry of the face. Most patients exhibit hyperextension of the cervical portion of the spine (lordosis), which may become so extreme in certain cases of basilar impression that the occiput seems to rest on the posterior aspect of the neck.

McRae and Barnum (1953) report on 25 patients with occipitalization of the atlas, of which 18 are symptomatic. It is of interest that only one

patient has the clinical finding of head tilt. They note that "except for the assimilated vertebra the skull was surprisingly normal."

However, they also state:

The presence of associated congenital abnormalities was noted in 5 cases (20 per cent). These included hypoplasia of the jaw, incomplete cleft of nasal cartilage, hypospadias, cleft palate, congenital deformity of the external ear, cervical rib and incomplete rotation of the kidney with anomalous renal vessels.

Spillane, Pallis, and Jones (1957) report a study of 24 neurologically disabled patients with bony and/or neural anomalies of a developmental nature in the region of the foramen magnum, of which "about half of these patients presented abnormal configurations of the head and neck." Seven patients have occipitalization of the atlas (two in conjunction with Klippel-Feil syndrome, also called congenital cervical synostosis); the other patients possess abnormalities including basilar impression, cervical vertebral fusion, atlanto-axial dislocation, and cerebellar ectopia consistent with the Arnold-Chiari deformity.

They make the following observations concerning clinical appearance:

Patients with craniovertebral anomalies often have short necks or some abnormality of posture of the head, especially if there is occipitalization of the atlas. Fusion of cervical vertebrae and basilar impression may be present in patients with necks of normal configuration. Certain stigmata are not uncommon: facial asymmetry; malformed ears; defective palates, congenital absence of thenar muscles; congenital absence of digits.

Occipitalization of the atlas was present in 5 of the 6 cases with noticeable tilting of the head. Bertolotti (1920) and Feil (1921) were among the first to comment on "bony torticollis" and considered that the tilt resulted from the asymmetrical synostosis of the lateral masses of the atlas to the base of the skull. In our cases, asymmetrical basilar invagination was occasionally associated with tilting of the head. In one of our patients, unequal development of the axis vertebra seemed to be responsible. No instances of cervical hemivertebra or of "paramastoid process" of the occipital bone were encountered--defects sometimes found in association with craniovertebral anomalies and said to produce a head tilt.

In the 2 cases in which the neck was grossly short, the characteristic radiological features of the Klippel-Feil Syndrome were present.

Otherwise, an abnormally short neck could not be correlated with any specific type of cranio-vertebral anomaly. No patient, however, with occipitalization of the atlas had a normal-looking neck.

Bharucha and Dastur (1964) present case histories of 40 patients with craniovertebral anomalies at K.E.M. Hospital, Bombay, India. Of the 40 patients, 23 have occipitalization of the atlas, 6 have basilar invagination, 4 have atlanto-axial dislocation with a separate odontoid process, 6 have atlanto-axial dislocation with an intact odontoid process, and one has an unassimilated rudimentary atlas. Differing from other studies, trauma and/or infection may have contributed significantly to the bony anomaly in many of these patients or at least to their neurological manifestations. Of note, facial asymmetry or other abnormal facial characteristics are not mentioned, and little is said about neck or head posture. Regarding physical features of the head and neck, they write:

A short neck and low hair line were most frequent with occipitalization, being present in 19 cases; of these, 16 had restricted neck movements. In one case of occipitalization, restricted neck movements and torticollis were present, but he did not appear to have a short neck. Among the dislocations only 1 had a short neck, but in 6 neck movements were restricted. Two cases of basilar invagination and the only case of rudimentary atlas had short necks.

## MATERIALS AND METHODS

### Selection of Skull Material

In the dry skull collection at the University of Texas Health Science Center at Houston Dental Branch, there are 18 skulls which bear the anomaly called occipitalization of the atlas. Of these, 12 are adult skulls, 4 young adult/late adolescent skulls, and 2 child skulls. The two child skulls were excluded from the study because of the significant size discrepancy, incomplete growth, the inability to find comparable normal child skulls, and the potential skewing of the statistical analysis.

Comparable normal skulls for each of the remaining 16 occipitalized skulls were selected from the dry skull collection, based on a corresponding cranial index. The cranial index is defined as the greatest breadth of the cranium measured in centimeters divided by the greatest antero-posterior length of the cranium in the midline measured in centimeters, multiplied by 100. These measurements were performed with anthropologic calipers, accurate to one-tenth of a centimeter. The goal was to establish pairs of occipitalized and normal skulls with identical cranial indices, as well as identical length and breadth of the crania, or as close as possible, to assure comparable size and shape of the two groups of skulls. Normal skulls which had insufficient teeth to establish centric occlusion, thereby making it difficult to position the mandible exactly, were excluded from the study. Skulls that were damaged or missing significant parts were also excluded. Table 1 indicates the matched pairs of occipitalized and normal skulls with related cranial index data.

TABLE 1. CRANIAL INDICES OF PAIRED SKULLS

Skull I.D. Number <sup>1</sup>	Cranial Index	Breadth (in cm.)	Length (in cm.)
0 - 1	71.6	12.6	17.6
N - 11	71.8	12.5	17.4
0 - 2	83.4	13.1	15.7
C.I. - 143	85.6	13.1	15.3
0 - 3	80.1	13.3	16.6
C.I. - 117	80.1	13.3	16.6
0 - 4 <sup>2</sup>	73.05	12.2	16.7
N - 19 <sup>2</sup>	73.3	12.1	16.5
0 - 5	69.4	12.7	18.3
C.I. - 125	69.6	12.6	18.1
0 - 6	83.85	13.5	16.1
C.I. - 126	81.4	13.6	16.7
0 - 9	69.7	12.2	17.5
C.I. - 140	69.9	12.3	17.6
0 - 10	75.3	12.5	16.6
C.I. - 107	73.15	12.4	16.5
0 - 11	79.5	13.2	16.6
C.I. - 101	78.6	13.2	16.8

TABLE 1. CRANIAL INDICES OF PAIRED SKULLS (Continued)

Skull I.D. Number <sup>1</sup>	Cranial Index	Breadth (in cm.)	Length (in cm.)
0 - 12	80.0	14.0	17.5
C.I. - 103	81.0	14.1	17.4
0 - 13	75.9	12.6	16.6
C.I. - 118	75.9	12.6	16.6
0 - 14 <sup>2</sup>	75.1	13.3	17.7
C.I. - 123	75.4	13.5	17.9
0 - 15 <sup>2</sup>	65.3	12.6	19.3
C.I. - 132	66.1	12.5	18.9
0 - 16 <sup>2</sup>	74.4	12.8	17.2
Y - 7 <sup>2</sup>	74.4	12.8	17.2
0 - 17	68.3	12.7	18.6
C.I. - 144	69.9	12.8	18.3
0 - 18	77.2	14.2	18.4
C.I. - 106	76.2	13.8	18.1

<sup>1</sup>Skull numbers beginning with letter "0" indicate occipitalized skulls; all other skulls are normal.

<sup>2</sup>Young adult/late adolescent skulls; others are adult skulls.

### Preparation of the Skulls

All metallic objects, such as screws, springs and identification plates, were removed from the skulls. Segments of 0.050 inch wire lead solder were adapted to the intracranial surface of the clivus, extending around the anterior margin of the foramen magnum and onto the basi-occiput in the midline, to aid in defining these areas radiographically. On occipitalized skulls, a midline foramen or cleft was present at the anterior junction of the atlas to the occiput to allow for placement of this wire. In addition, a strip of wire solder was placed on the inferior anterior rim of the fused atlas in the midline. The lead solder wires were attached with cellophane tape.

The mandibles were then fixed to the skulls by placing white, soft dental "beading" wax into the temporomandibular joint space. Dental "sticky" wax was placed in the bicuspid regions to lute the maxillary and mandibular teeth to one another. Care was taken to make sure the teeth were in their maximum intercuspation, taking into account wear facets on the teeth and proper temporomandibular joint spacial relationships.

### Radiographic Technique

Right lateral and posterior-anterior cephalometric radiographs were made of each occipitalized and normal skull, using the Quint X-ray Sectograph, located in the Dental Radiology Department at the Dental Branch. The skulls were supported in the head positioning device of the Sectograph, by inserting the ear rods into the external auditory meati of the skulls. The skulls were mounted so that the line from the most superior point of the external auditory meatus (Porion) to the most inferior point on the inferior orbital rim (Orbitale) was oriented in a true horizontal position (Frankfort Horizontal). To assure accurate positioning, a small bubble-type line level, made by

Stanley Tools, was held along the Frankfort Horizontal on each side of the skull, when the skulls were fixed into position. To avoid tilting of the skulls in a frontal plane, the line between right and left Orbitale was oriented in a true horizontal plane with the aid of the line level. After the skulls were properly positioned, strips of cellophane tape secured the zygomatic arches to the supports of the head positioning unit to prevent rotation of the skulls around the ear rods.

After the skulls were properly positioned, right lateral and posterior-anterior cephalometric radiographs were exposed. The radiographic unit employed was the Quint X-ray Sectograph, using the following exposure settings: KVP - 64 kilovolts, 200 milliamperes, exposure time - 2/15 seconds. The radiographic film used was Kodak X-OMAT L Film (XL-1), 10 x 12 inches in dimension. A medium speed screen was placed in the cassettes. The exposed film was developed in the Litton Automatic Processor, Model P-10, using Kodak RP developer and fixer and a five-minute processing cycle.

Prior to exposing the whole series of skulls, a representative skull was selected to establish standardized radiographic exposure settings. Keeping the milliamperage constant at 200 milliamperes, various KVP and time combinations were tried, attempting to get the best quality of radiograph in terms of clarity, contrast, and visibility of pertinent structures, resulting in the selected settings mentioned in the previous paragraph.

#### Cephalometric Tracings and Determinants

A sheet of transparent matte acetate, 0.003 inches in thickness, measuring 10 by 12 inches was affixed to each radiograph with cellophane tape. Pertinent structures were traced from the radiograph onto the matte acetate, using a sharp No. 2 pencil. Several significant radiographic points were

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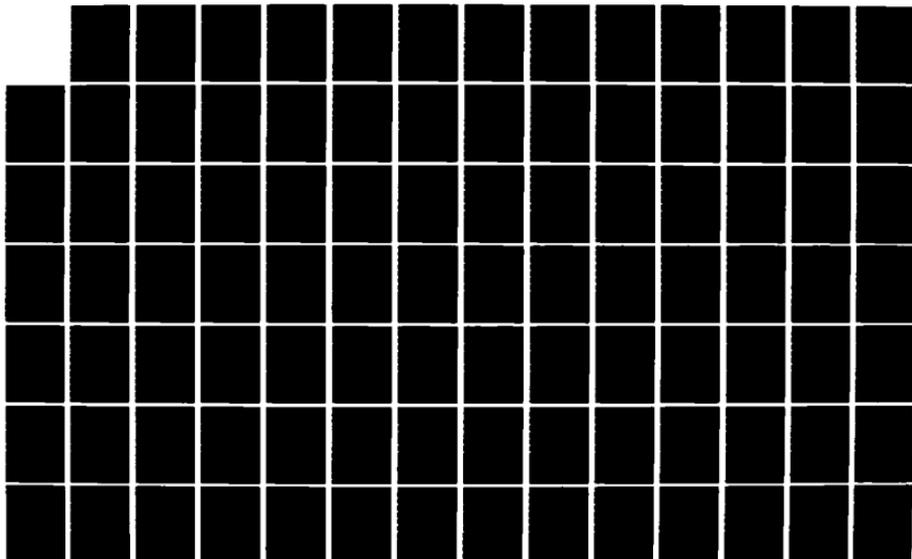
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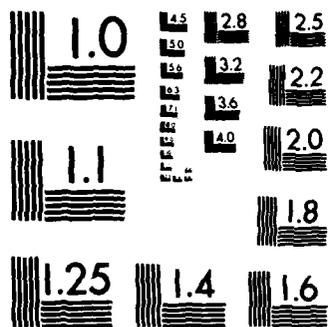
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transposed onto the tracing. From these points, certain reference lines were drawn, and angular and linear measurements were taken.

The roentgenocephalometric landmarks or points are defined below. Their definitions, which pertain primarily to the lateral view, are paraphrased from these sources: Howells (1937), Salzmann (1966), van der Linden (1971), Hinds and Kent (1972), and Rocky Mountain Data Systems, Inc.

Basion (Ba) - The most inferior posterior point on the anterior rim of the foramen magnum (located in the midline).

Derived Basion (DBa) - new term - the corresponding point as Basion on an occipitalized skull where Basion cannot be defined exactly.

Pseudo-Basion (PBa) - new term - on an occipitalized skull, the most inferior posterior point on the anterior rim of the fused atlas (located in the midline).

Opisthion (Op) - the posterior midsagittal point on the posterior margin of the foramen magnum.

Nasion (N) - the most anterior point of the nasofrontal suture seen on a lateral cephalogram.

Sella (S) - the center or midpoint of the hypophyseal fossa of the sphenoid bone, selected by inspection.

Porion (P) - the most superior point of the external auditory meatus.

Orbitale (Or) - the most inferior point on the inferior orbital rim.

Pogonion (Po) - the most anterior midsagittal point of the mandibular symphysis.

Menton (Me) - the most inferior midline point of the mandibular symphysis.

Gnathion (Gn) - the midpoint between the most anterior point (Pogonion) and the most inferior point (Menton) of the mandibular symphysis.

Gonion (Go) - the most inferior posterior point on the angle of the mandible, obtained by bisecting the angle formed by tangents to the lower and posterior borders of the mandible.

Pterygoid Point (Pt) - the intersection of the inferior border of the foramen rotundum with the posterior wall of the pterygomaxillary fossa (fissure).

Point A - also called Subspinale (pA or A) - the deepest point of the midline concavity of the anterior maxillary alveolar process (anterior surface) between the Anterior Nasal Spine and the alveolar crest.

Point B - also called Supramentale (pB or B) - the deepest point of the midline concavity of the mandibular alveolar process (anterior surface) between the mental protuberance (or chin) and the alveolar crest.

Tip of the Anterior Nasal Spine - also called Acanthion (ANS) - the most anterior point on the median sharp bony process of the maxilla at the lower margin of the anterior nasal opening.

Tip of the Posterior Nasal Spine (PNS) - the most posterior point on the median sharp bony process, formed by the united projecting ends of the posterior borders of the palatal processes of the palatine bones.

Using these points, the following reference lines and functional measurement lines were drawn on the right lateral cephalogram. These lines deal with cranial base relationships, the cephalometric analysis advocated by Ricketts, and the cephalometric analysis fostered by Steiner. In occipitalized skulls where lines involving Basion (Ba) are normally used, separate lines drawn to Derived Basion (DBa) and Pseudo-Basion (PBa) were substituted.

Sella-Nasion line (SN) - a line between Sella and Nasion, used in determining the basal angle and as a reference line in the Steiner analysis.

Sella-Basion line (SBa) - a line between Sella and Basion, used in determining basal angle. (SDBa and SPBa on occipitalized skulls)

Posterior Nasal Spine - Opisthion line (PNS-Op), Chamberlain's line - a line from the tip of the Posterior Nasal Spine to the posterior rim of the foramen magnum, used in the evaluation of basilar impression.

Nasion-Basion line (NBa), Huxley's line - a line from Nasion to Basion, used as a reference line in the Ricketts analysis, also used in evaluating cranial base relationships. (NDBa and NPBa on occipitalized skulls)

Frankfort Horizontal (FH) - a line from Orbitale to Porion, used as a reference line in the Ricketts analysis.

Nasion-Pogonion line (NPo) - a line from Nasion to Pogonion, used in the Ricketts analysis, designated as the facial plane.

Pterygoid Point - Gnathion line (PtGn) - a line from Pterygoid Point to Gnathion, used in the Ricketts analysis, also called the facial axis by Ricketts.

Gonion-Gnathion line (GoGn), also called the mandibular plane - a line from Gonion to Gnathion, used in the Steiner analysis. In the Ricketts analysis, a Gonion-Menton line is used. However, for standardization and simplification, the GoGn line was utilized in the Ricketts analysis as well.

Nasion-Point A line (NA) - a line drawn from Nasion to Point A (or Subspinale), used in Steiner analysis for orientation of the maxilla in an anterior-posterior direction.

Nasion-Point B line (NB) - a line drawn from Nasion to Point B (or Supramentale), used in the Steiner analysis for orientation of the mandible in the anterior-posterior direction.

On the posterior-anterior cephalogram, two additional reference lines were drawn, besides the tracing of significant anatomical structures of the

face and the base of the skull. These lines deal with cranial base relationships, particularly basilar impression, which were advocated by Fischgold and Metzger (Spillane, Pallis, and Jones, 1957).

Mastoid Line (ML) - a line drawn between the inferior tips of the right and left mastoid processes, also called Fischgold's line.

Digastric Line (DGL) - a line drawn between right and left digastric grooves which are located at the junction of the medial aspect of the mastoid processes with the base of the skull.

#### Measurements

Using the series of points and lines mentioned above, angular and linear measurements were obtained from the cephalometric tracings of the 16 occipitalized skulls and 16 normal skulls. These measurements can be organized in four basic categories: (1) cranial base relationships; (2) Ricketts cephalometric analysis (Ricketts, 1960a; Ricketts, 1960b; Ricketts, 1975; Ricketts, Bench, Hilgers, Schulhof, 1972; Ricketts, Schulhof, Bagha, 1976; Rocky Mountain Data Systems, Inc.); (3) Steiner cephalometric analysis (Steiner, 1953; Hinds and Kent, 1972); (4) facial height assessment (Hinds and Kent, 1972). It is noted that only skeletal relationships are considered; dental relationships have been omitted. Regarding measurements on occipitalized skulls in which Basion is involved, separate measurements substituting Derived Basion and Pseudo-Basion were taken.

#### CRANIAL BASE RELATIONSHIPS:

Nasion-Sella-Basion angle (N-S-Ba), basal angle - the inferior anterior angle formed by the intersection of the Sella-Nasion line with the Sella-Basion line, subtended at Sella. Mean:  $129^{\circ}$ ; range:  $114-144^{\circ}$  (Ricketts, 1960a).

For occipitalized skulls, Nasion-Sella-Derived Basion angle (N-S-DBa) and Nasion-Sella-Pseudo-Basion angle (N-S-PBa) were taken.

Length of Sella-Nasion (S-N(mm)) - the linear measurement between points Sella and Nasion measured in millimeters, the length of the anterior cranial base.

Length of Sella-Basion (S-Ba(mm)) - the linear measurement between points Sella and Basion measured in millimeters, the length of posterior cranial base or clivus. For occipitalized skulls, the length of Sella-Derived Basion (S-DBa(mm)) was measured; no measurement to Pseudo-Basion was recorded.

Sella-Basion length: Sella-Nasion length ratio (S-Ba:S-N x 100) - the length of Sella-Basion (S-Ba(mm)) divided by the length of Sella-Nasion (S-N(mm)), multiplied by 100. The length of Sella-Derived Basion (S-DBa(mm)) was used in occipitalized skulls.

Relationship of Basion to Chamberlain's line (Ba-PNSOp(mm)) - the shortest distance between Basion and the line from the tip of the Posterior Nasal Spine to Opisthion, measured in millimeters. A positive value indicates that Basion is cephalad to this line; a negative number, Basion is caudad to the line. Derived Basion (DBa) was the measurement point for occipitalized skulls; the measurement involving Pseudo-Basion (PBa) was not taken.

Relationship of Basion to the Mastoid Line (Ba-ML(mm)) - the shortest distance between Basion and the Mastoid Line on the posterior-anterior cephalometric tracing, measured in millimeters. A positive value indicates that Basion is cephalad to the reference line, while a negative number indicates that Basion is caudad to this line. The measurements of Derived Basion (DBa) and Pseudo-Basion (PBa) to the Mastoid Line were performed on occipitalized skull tracings.

Relationship of Basion to the Digastric Line (Ba-DGL(mm)) - the shortest distance between Basion and the Digastric Line on the posterior-anterior

cephalometric tracing, measured in millimeters. A positive value indicates that Basion is caudad to the reference line, while a negative value indicates that Basion is cephalad to this line. The measurements of Derived Basion (DBa) and Pseudo-Basion (PBa) to the Digastric Line were performed on occipitalized skull tracings.

Relationship of the Occipital Condyle to the Digastric Line (OC-DGL(mm)) - the shortest distance between the most inferior point of the more cephalad occipital condyle and the Digastric Line on the posterior-anterior cephalometric tracing, measured in millimeters. A positive value indicates that the occipital condyle is caudad to this reference line, while a negative number indicates that the occipital condyle is cephalad to this line. When the occipital condyle is fused to the atlas, the most inferior point of the invagination of the cortical plates between the occipital condyle and the atlas was used. Mean value of normal individuals (McRae, 1971) is 11 mm. ( $\pm 4$  mm.).

Nasion Basion - Frankfort Horizontal Angle (NBa-FH) - the anterior acute angle formed by the intersection of the Nasion-Basion line (NBa) with the Frankfort Horizontal line (FH), called angle of cranial deflection in Ricketts analysis, with a norm of  $27 \pm 3^\circ$  (Rocky Mountain Data Systems, Inc.). For occipitalized skulls, angles formed by Nasion-Derived Basion (NDBa) and Nasion-Pseudo-Basion (NPBa) with Frankfort Horizontal were measured.

Sella Nasion - Frankfort Horizontal Angle (SN-FH) - the anterior acute angle formed by the intersection of the Sella-Nasion line with the Frankfort Horizontal line. Mean value -  $9.80^\circ$  with a standard deviation of  $2.81^\circ$  (Moore, 1976).

## RICKETTS CEPHALOMETRIC ANALYSIS:

Frankfort Horizontal - Nasion Pogonion Angle (FH-NPo) - the inferior, posterior angle formed by the intersection of the Frankfort Horizontal line with the Nasion-Pogonion line, indicative of facial depth, also called the facial plane angle. Norm:  $90 \pm 3^{\circ}$  (Rocky Mountain Data Systems, Inc.).

Nasion Basion - Pterygoid Point Gnathion Angle (NBa-PtGn) - the inferior, posterior angle formed by the intersection of the Nasion-Basion line (NBa) with the Pterygoid Point-Gnathion line (PtGn), referred to as the angle of facial axis. Norm:  $90 \pm 3.5^{\circ}$  (Rocky Mountain Data Systems, Inc.). For occipitalized skulls, angles involving the Nasion-Derived Basion line (NDBa) and the Nasion-Pseudo-Basion line (NPBa) with the Pterygoid Point-Gnathion line were measured.

Frankfort Horizontal-Gonion Gnathion Angle (FH-GoGn) - the anterior acute angle formed by the intersection of the Frankfort Horizontal line with the Gonion-Gnathion line, called the mandibular plane angle. This is a slight variation from the standard Ricketts measurement, which uses a line drawn from Gonion to Menton instead, for determining the mandibular plane. Norm:  $23 \pm 4.5^{\circ}$  (Rocky Mountain Data Systems, Inc.).

Relationship of Point A to the Nasion-Pogonion Line (pA-NPo(mm)) - the shortest distance between Point A and the Nasion-Pogonion line, measured in millimeters; a positive value indicates that Point A is anterior to the Nasion-Pogonion line, and a negative number indicates that Point A lies posterior to this line. This measurement determines the convexity of the face. Norm:  $0 \pm 2$  mm. (Rocky Mountain Data Systems, Inc.).

## STEINER CEPHALOMETRIC ANALYSIS:

Sella-Nasion-Point A Angle (SNA) - the posterior inferior angle formed by the intersection of the Sella-Nasion line (SN) with the Nasion-Point A line (NA), subtended at Nasion, measuring the anterior-posterior position of the maxilla to the cranial base. Norm:  $82 \pm 3^{\circ}$  (Hinds and Kent, 1972; Steiner, 1953).

Sella-Nasion-Point B Angle (SNB) - the posterior inferior angle formed by the intersection of the Sella-Nasion line (SN) with the Nasion-Point B line (NB), subtended at Nasion, relating the anterior-posterior position of the mandible to the cranial base. Norm:  $80 \pm 4^{\circ}$  (Hinds and Kent, 1972; Steiner, 1953).

Point A-Nasion-Point B Angle (ANB) - the inferior acute angle formed by the intersection of the Nasion-Point A line (NA) with the Nasion-Point B line (NB), subtended at Nasion, indicating the anterior-posterior relationship of the mandible to the maxilla. The ANB angle is positive when the NA line is anterior to the NB line and negative when the reverse is true. Norm:  $2 \pm 2^{\circ}$  (Hinds and Kent, 1972; Steiner, 1953).

Sella Nasion-Gonion Gnathion Angle (SN-GoGn) - the anterior acute angle formed by the intersection of the Sella-Nasion line (SN) with the Gonion-Gnathion line (GoGn), also referred to as the mandibular plane angle. Norm:  $32^{\circ}$  (Steiner, 1953);  $35 \pm 5^{\circ}$  (Hinds and Kent, 1972). From the drawings in the Hinds and Kent text, it appears that they used a Gonion to Menton mandibular plane which may account for the differences of the cited norms.

There is one other angular measurement, which is not a part of either the Ricketts or the Steiner analysis, that was included for the sake of completeness.

Nasion Basion-Gonion Gnathion Angle (NBa-GoGn) - the anterior acute angle formed by the intersection of the Nasion-Basion line (NBa) with the Gonion-Gnathion line (GoGn), another mandibular plane angle using Huxley's line. For occipitalized skulls, angles formed by the Nasion-Derived Basion line (NDBa) and the Nasion-Pseudo Basion line (NPBa) with the Gonion-Gnathion line (GoGn) were measured.

#### FACIAL HEIGHT ASSESSMENT:

To evaluate facial height, a vertical line was drawn from Nasion, perpendicular or at a right angle to the Frankfort Horizontal line. Certain anatomical points were translated to this "Frankfort Vertical" in a right-angle fashion so that the anterior-posterior extension of these points was parallel to the Frankfort Horizontal line. Linear measurements between points and ratios of linear measurements were obtained. The ratios were calculated by dividing a vertical mid-face length by a vertical lower facial height, multiplied by 100 (in order to provide values in whole numbers).

Nasion - Point A Length (N-pA(mm)) - the distance between Nasion and Point A on the Frankfort Vertical line, measured in millimeters.

Point A - Pogonion Length (pA-Po(mm)) - the distance between Point A and Pogonion on the Frankfort Vertical line, measured in millimeters.

Nasion - Point A: Point A - Pogonion Ratio (N-pA:pA-Po x 100) - the ratio of the length from Nasion to Point A to the length from Point A to Pogonion, multiplied by 100. The normal value is a ratio of 8:7 (Hinds and Keat, 1972). In this study, this ratio is presented in decimals multiplied by 100, or a value of 114.

Nasion - Anterior Nasal Spine Length (N-ANS(mm)) - the distance between Nasion and the tip of the Anterior Nasal Spine on the Frankfort Vertical line, measured in millimeters.

Anterior Nasal Spine - Menton Length(ANS-Me(mm)) - the distance between the tip of the Anterior Nasal Spine and Menton on the Frankfort Vertical line, measured in millimeters.

Nasion-Anterior Nasal Spine: Anterior Nasal Spine - Menton Ratio

(N-ANS: ANS-Me x 100) - the ratio of the length from Nasion to the tip of the Anterior Nasal Spine to the length from the tip of the Anterior Nasal Spine to Menton, multiplied by 100. Hinds and Kent (1972) suggested a similar ratio, but they used the measurement from the tip of the Anterior Nasal Spine to Gnathion for the lower face length instead. The norm as stated by Hinds and Kent is 7:9. When represented as a decimal multiplied by 100, this value is 77.8.

#### Statistical Analysis

The data obtained from these linear and angular measurements were analyzed statistically using the Hewlett-Packard 2000 Access Basic computer, located within the Dental Branch. For each measurement from the 16 occipitalized skulls (Group A) and the 16 normal skulls (Group B or control group), basic statistical data consisting of the mean, standard deviation, standard error, and coefficient of variation were calculated, using the program entitled "STATS". In addition, the data from the 16 occipitalized skulls and 16 normal skulls were subdivided into the 12 adult skulls and their normal counterparts and the 4 adolescent skulls and their paired skulls. Basic statistics were obtained from the measurements from each of these subsets of 12 adult occipitalized skulls, 12 normal adult skulls, the 4 adolescent

occipitalized skulls, and the 4 normal skulls paired to the 4 adolescent occipitalized skulls. The possibility that incomplete growth of the four adolescent occipitalized skulls might grossly affect the statistical significance of this study dictated that the data should be evaluated both including and excluding the adolescent skulls.

Since occipitalized skull O-2 was lacking the anterior arch of the fused atlas, measurements involving the point Pseudo-Basion could not be obtained. Therefore, the sample size for those measurements was 15 for all occipitalized skulls and 11 for adult occipitalized skulls.

The basic statistical data of the measurements for Group A (occipitalized skulls) and Group B (normal skulls) were subjected to the Students "T" Test and the Mann-Whitney "U" Test to determine if the differences in data between the two groups were statistically significant. Within Group A, data involving Derived Basion and Pseudo-Basion were compared to one another using the Students Paired "T" Test and Mann-Whitney "U" Test. Regarding the Students Paired "T" Test, data from skull O-2 and its normal counterpart were omitted. The computer program for the Students "T" and Paired "T" Tests provided a Students "T" value number and its probability. The Mann-Whitney "U" Test program provided a "U" value only, which required reference to a "U" value table to ascertain the probability. (See Appendix.)

To determine how basilar skull measurements influence facial skeletal parameters, the data in Group A (occipitalized skulls) and in Group B (normal skulls) were subjected to a multiple regression/correlation analysis. This computer program has the code name "MULREG". The same twenty-five measurements (or variables) were selected from each group, none involving Pseudo-Basion. The individual data points for these 25 selected measurements from each of the 16 occipitalized skulls and 16 normal skulls were entered into

the computer as two separate analyses (one for Group A data and one for Group B). The computer program provided correlation coefficients and regression indices for each of the 25 measurements.

## DESCRIPTION OF SKULLS WITH ATLANTAL OCCIPITALIZATION

The skull collection at University of Texas Health Science Center at Houston Dental Branch contains 18 skulls bearing various characteristics of atlanto-occipital fusion. These skulls are designated by the symbols 0-1 through 0-18. According to age, the skulls are listed as follows:

	<u>Sample Size</u>	<u>Designation</u>
Child	2	0-7, 0-8
Youth	4	0-4, 0-14, 0-15, 0-16
Adult	12	The remainder

The criterion for the designation of adult skulls is based on the complete calcification of the spheno-occipital synchondrosis, therefore assuming that skeletal growth is complete. The skulls designated as youth skulls, which are estimated to be between 15 and 18 years of age, have noncalcified or incompletely calcified spheno-occipital synchondroses, but eruption of all permanent teeth, with the exception of the third molars, had occurred. These teeth, however, display partial root formation within their crypts. The child skulls are small, having wide open spheno-occipital synchondroses, and deciduous dentition, without evidence of eruption of the first permanent molars, indicating that these skulls are 3-6 years of age. Due to their deficient development and immaturity, these two child skulls (0-7, 0-8) are excluded from this study. Adult skulls designated as 0-2 and 0-17 have other cranial or cervical skeletal abnormalities. Detailed description of each adult and adolescent atlantally fused skull is presented.

Adult SkullsSkull 0-1

The imperfect atlas is fused or assimilated into the occiput in an asymmetrical manner. The right side tends to be assimilated, while the left side tends to be fused. On the right side, the anterior arch, the lateral mass and the posterior arch are fused to the margin of the foramen magnum. The anterior atlanto-occipital space is absent on the right side; however, there is evidence of a slight groove on the interior aspect of the anterior arch which leads into a "blind foramen", superior to the inferior articulating surface of the atlas. On the left side, there is a definite anterior atlanto-occipital space, measuring 1 mm. in width, from the midline to the antero-medial aspect of the lateral mass. A prominent median tubercle extends from the inferior surface of the anterior arch. There is a definite round concave facet on the internal surface of the anterior arch for the articulation of the odontoid process of the axis.

The left lateral mass extends further inferiorly than the right lateral mass. The superior aspects are thoroughly fused to the occiput. The inferior articular surfaces are round to slightly ovoid, slightly concave and project in a medial, posterior, inferior direction.

The posterior arch is imperfect on the right side, leaving a 3 mm. gap at its distal extremity. The right neural arch is fused to the occiput except for the posterior 2 mm. of the distal extremity. There is a lateral atlanto-occipital foramen between the fused posterior arch and the lateral mass for the passage of the right vertebral artery. The left half of the posterior arch is free from the occiput, although the distal two-thirds of the posterior arch is enlarged superiorly to within 1 mm. of contacting the base of the skull. The left posterior lateral rim of the foramen magnum exhibits

notching, which may be artifactual. A large dilatation of the posterior lateral atlanto-occipital space is present near the lateral mass, presumably for the left vertebral artery.

The transverse processes are well-developed, each possessing an oval foramen transversarium. The costal and transverse elements are intact. The left transverse process is free, although there is a thickening and elongation of a paramastoid process projecting from the occipital bone. The right transverse process approximates the base of the skull at its extremity and is fused at its posterior edge to the base of the skull. A foramen between the fused distal extremity and the lateral mass thus is formed for the right vertebral artery, which exits the foramen transversarium in a tortuous fashion to pass through this foramen and enters the foramen magnum through the lateral atlanto-occipital foramen previously described.

The hypoglossal foramina are located in their normal relationship to the fused occipital condyles, tunneling antero-laterally from the rim of the foramen magnum, superior to the fused atlantal lateral mass--occipital condyle complex, exiting above this fusion near the jugular foramen. There is a bony spur projecting from the superior aspect of the canal, tending to divide the hypoglossal canal into anterior and posterior foramina. Other "blind foramina" are noted in the posterior condyloid regions bilaterally and on the internal aspect of the lateral masses adjacent to or within the fusion line.

The fused atlas is slightly rotated to the right. The median tubercle on the anterior arch is rotated slightly to the right of the midline of the clivus. The right transverse process is directed toward the right mastoid process, while the left transverse process is directed in front of the left mastoid process. As stated previously, the left lateral mass is larger than

the right, projecting further caudally. These fused orientations of the skull on the atlas tend to produce a leftward rotation and a rightward tilting of the skull in its anatomical position.

#### Skull 0-2

This skull is markedly asymmetrical, exhibiting multiple cranio-facial anomalies, besides occipitalization of the atlas. The skull demonstrates marked left occipito-parietal bossing and marked hypoplasia of the left zygomatic arch, the left zygomatic bone (decreasing the size of the left orbit), and the left side of the mandible. The mandibular deficiency is composed of left condylar hypoplasia, with a poorly-developed left ramus, coronoid process and corpus. The mental protuberance is deviated to the left side. The dentition, although rotated to the left of the midline, maintains a normal Class I occlusal relationship with excellent intercuspation. The anterior maxillary teeth are inclined to the left to accommodate the deviated mandible. In relation to the left occipito-parietal bossing, the left mastoid process is 10 mm. farther removed from the foramen magnum than is the right side. The left mastoid process is larger than the right. The digastric notch is deeper and more pronounced on the left side. There are two grossly enlarged posterior mastoid foramina on the left, which are separated by a fine spicule of bone. These foramina become confluent internally, forming a large cavity suggestive of the presence of a venous lake or sinus. On the internal surface, this cavity enters the lateral aspect of the groove for the transverse sinus, as it turns medially and inferiorly to become the indentation for the sigmoid sinus.

The atlanto-occipital complex is very asymmetrical as well. The right side exhibits features of classical occipitalization of the atlas, while the left side bears equivocal morphologic features. These anomalous findings

may represent a manifestation of an occipital vertebra, an abnormally formed occipital condyle, or an atypical pattern of assimilation of the atlas.

The right side of the fused atlas is composed of only a lateral mass, a transverse process and a small projecting spur of a posterior arch. The lateral mass is completely fused to the occiput; however, an irregular horizontal groove is present on its internal surface below the hypoglossal canal. The inferior articular surface is reniform in shape, and slightly concave, bearing a posterior lip projecting caudally. The facet is directed medially and inferiorly, extending approximately 12 mm. more inferiorly from the base of the skull than the opposite articulating surface.

The diminutive transverse process on the right side is fused to a paracondyloid process at its distal extremity. Lines of fusion are present at this point of aberrant ossification, as well as at the junctions of the costal and transverse elements of the transverse process to the lateral mass. In addition to the atlantally fused paracondyloid process, there is a sharp spur projecting inferiorly from the posterior rim of the jugular foramen toward the costal element of the atlas. This projecting spur lacks contact with the transverse process by approximately two millimeters.

The foramen transversarium is completely formed and communicates with a horizontally directed foramen between the fused distal extremity and the lateral mass. There is a groove on the posterior surface of the lateral mass between the remnants of the posterior arch and the base of skull for passage of the vertebral artery.

For all practical purposes, the posterior arch is missing. A small posterior projection from the right transverse process at its origin from the lateral mass represents the residual posterior arch. On its distal aspect, there is a caudally directed, roughened surface which may indicate an area of

synchondrosis of the incompletely fused posterior arch to the lateral mass, or the presence of fracture of the posterior arch during previous handling. The right lateral and posterior rim of the foramen magnum is smooth, suggesting that fusion of the posterior arch to the base of the skull had not occurred.

The left side of the atlanto-occipital complex consists primarily of a large elongated, convex, articulating surface. This condylar articulating surface originates close to the anterior midline of the foramen magnum, inclined in a postero-lateral direction. Its greatest length measures 28 mm., and its width approximates 10 mm. The posterior lateral extent ends in a large depression lateral to the foramen magnum. The articular surface is tri-directional, having portions which face medio-posteriorly, latero-anteriorly, and postero-laterally. The postero-lateral surface tends to be slightly concave, ending in a caudally projected spine, suggestive of a para-condyloid process. This posterior, lateral articulating element tends to cover the posterior portion of the jugular foramen. At the posterior margin of this postero-lateral facet, there is an anteriorly directed, transverse fissure, ending in a "blind" cavity. From this fissure, lines of fusion are observed to traverse the postero-lateral articulating surface near the para-condyloid process and extend into the bridged jugular foramen. These lines of fusion extend medially into the foramen magnum and course the internal surface of the condylar process in the region of the hypoglossal canal.

At the anterior midline border of the foramen magnum, there is a hiatus or absence of the median portion of the anterior arch of the atlas, measuring 4 mm. In a basal view, this hiatus makes the condylar and lateral masses appear to be set upon pedestals. To the right of the hiatus, there is an irregular, bony ridge extending into the right lateral mass. This ridge is suggestive of a persistent occipital vertebral remnant.

Skull 0-3

This skull has a well-developed atlas which is fused to the occipital bone at the lateral masses bilaterally and at the proximal right posterior arch. The anterior arch is well-developed and separated from the basi-occiput by a fine anterior atlanto-occipital space, extending to the lateral masses bilaterally. The anterior arch possesses a very prominent median tubercle on its anterior surface and a well-defined median facet on its posterior surface, measuring approximately 8 mm. in diameter, for the articulation of the odontoid process of the axis. This facet ends in a sharp inferior projection.

The lateral masses are fused over a wide base to the region of the occipital condyle. On the internal aspect there are fine lines of fusion, extending from the anterior atlanto-occipital space to the posterior aspect of the lateral masses. The inferior articulating surfaces are oval to reniform in shape and flat to slightly concave. These surfaces face medially and inferiorly; the left articulating surface has a slight posterior cant. The left lateral mass extends more inferiorly than the right. On the internal aspect there are enlarged, roughened projections for the attachment of the transverse ligament.

The transverse processes are well-formed and intact. The complete fusion of the costal and transverse elements form intact foramina transversaria. The distal extremities are enlarged and club-shaped. Neither transverse process is fused to the occiput; however, there are prominent paracondyloid processes projecting from the occipital bone at the posterior lip of the jugular foramen, greater on the right side. The gap between the transverse process and paracondyloid process on the right side measures 2 mm. The distal extremities are twisted in such way that the inferior surface faces a posterior-inferior direction.

The posterior arch is imperfect, having a gap of 12 mm. between the right and left distal extremities. The right arch is fused to the rim of the foramen magnum for a distance of 10 mm., located midway between the lateral mass and Opisthion. The fusion of the posterior arch to the occipital bone encloses the groove for the vertebral artery, producing a foramen entering into the spinal canal. The right distal extremity is free for a distance of 12 mm., ending in a flat club-like swelling. The left arch is free from fusion for its total extent. It is narrow at its origin from the lateral mass due to the presence of the large groove on its superior surface for the passage of the vertebral artery into the spinal canal. The distal extremity enlarges into a flat club-shaped extension, ending within 2 mm. of the rim of the foramen magnum. The posterior rim of the foramen magnum projects caudally as a 3 mm. ridge.

The foramina of the atlanto-occipital region are present in their normal position and of sufficient size. The hypoglossal canals pass antero-laterally superior to the fusion of the lateral masses. On the right side, between the inferior articulating surface and the crest for the attachment of the transverse ligament, a narrow, crescent-shaped foramen passes in a lateral direction through the apparent fusion of the lateral mass to the occiput, exiting posterior and inferior to the hypoglossal canal. The posterior condyloid foramen, the right larger than the left, passes from the external surface of the occipital bone, lateral to the foramen magnum, anteriorly through the occipital bone to enter the posterior aspect of the jugular foramen at its origin from the groove for the sigmoid sinus. The right jugular foramen seems to be enlarged considerably, taking on the form of a dilated venous sinus.

The orientation of the fused atlas to the occipital bone is noted to be asymmetrical. The skull is rotated to the left on its atlantal base. The

median tubercle of the anterior atlantal arch points to the right of the midline of the basi-occiput. The right transverse process is directed at the right mastoid process, while the left transverse process is directed toward the mandibular condyle. The rotation of the atlanto-occipital fusion and the increased cranio-caudal dimension of the left lateral mass cause the head to be twisted to the left with a slight rightward cant, when held in its neutral position.

#### Skull 0-5

The atlas is asymmetrically affixed to the base of the skull. The right side of the atlas appears to be assimilated into the rim of the foramen magnum. The left side of the atlas manifests as a classical form of fusion.

The anterior arch is well-developed, bearing a prominent median tubercle externally and a small facet for the articulation of the odontoid process of the axis internally. The anterior atlanto-occipital space is present only on the left side as an oval foramen, measuring 4 mm. in a cranio-caudal direction and 7 mm. in a transverse direction.

On the left side, the lateral mass is incompletely fused to occiput. The antero-medial portion of the lateral mass, adjacent to the anterior atlanto-occipital space, is calcified irregularly to the anterior rim of the foramen magnum, while the posterior two-thirds of the lateral mass is separated from the occipital condylar component by a fine cleft, filled either by cartilage or fibrous tissue. The left articulating surface is round to ovoid in shape and flat or slightly concave. It is inclined in a posterior, medial and inferior direction. Superior to the cleft between the lateral mass and occipital condylar element, sharp, rough projections protrude into the foramen magnum apparently for the attachment of the transverse ligaments.

The left transverse process is well-defined, possessing complete broad transverse and thin costal elements, thereby forming an intact foramen transversarium. At the distal aspect of the transverse element, a spur projects cephalad to contact a paracondyloid process originating from the occipital bone. The contact between these projections is not completely calcified, but appears as a suture containing cartilaginous or fibrous tissue. This contact, thus forming an antero-posteriorly directed foramen, encloses the vertebral artery as it winds toward the foramen magnum. The distal extremity is club-shaped and projects in a caudal direction.

The posterior arch is imperfect, exhibiting a 7 mm. gap at the posterior midline. The left half is free of fusion with the occipital bone; however, they are closely approximated. These apposed structures produce a canal for the passage of the vertebral artery into foramen magnum.

The right side appears to be assimilated throughout. The rudimentary posterior arch is incorporated into the rim of the foramen magnum. The groove or foramen for the passage of the vertebral artery between the atlas and occipital bone is lacking on the right side. There is a narrow "blind" fissure near the distal aspect of the posterior arch.

The right transverse process is well-incorporated into the paracondyloid region of the occipital bone. It presents as a large crest on the occipital bone, deficient in distinct transverse or costal elements. There is no evidence of a foramen transversarium or an antero-posteriorly directed passage for a vertebral artery. It appears that the vertebral artery on the right side is lacking or that it passed into the spinal canal at a lower interspace. The distal extremity of the right transverse process is represented by two inferiorly directed horns.

The right lateral mass is completely fused to the occiput. There are no lines of fusion present. Between the inferior articulating surface and the rugged attachment prominence for the transverse ligament is an irregular indentation. The inferior articulating surface is ovoid, much larger than on the left, and extends onto the anterior arch almost to the midline as a finger-like extension. The surface is basically flat or slightly concave, but has a mild convexity where the finger-like extension originates. These facets point in a posterior, medial, and inferior direction. Posterior to the inferior articulating facet, there is a shallow depression in the posterior arch which may represent the groove for the aberrantly located right vertebral artery.

The hypoglossal canal passes antero-laterally in its usual position and direction bilaterally. On the right side, a cluster of small foramina passes from an area lateral and inferior to the hypoglossal canal on the internal aspect of the foramen magnum and exits the skull through one foraminal orifice, inferior and lateral to the hypoglossal canal externally. In the region where the vertebral artery usually passes into the spinal canal between the atlas and occiput, there is a series of small foramina which course an anteriorly directed pathway into the jugular foramen. These foramina are representing the posterior condyloid foramen.

The skull is displaced to the right on the atlas, producing a transverse narrowing of the spinal canal by the internally protruding right lateral mass. The skull also appears to be rotated slightly to the right on the atlas. The distal extremity of the right transverse process is directed at the right mastoid process, while the left transverse process is directed toward the anterior aspect of the left external auditory meatus. Other

anomalous features of this skull include marked occipital bossing and an inordinate number of accessory bones in the lambdoidal suture.

#### Skull 0-6

This skull represents pure atlanto-occipital fusion without assimilation. The atlas is fused symmetrically to the occiput at the lateral masses and anterior arch. The anterior arch is completely fused to the basi-occiput except for the persistence of a median atlanto-occipital foramen, measuring approximately 2 mm. in diameter. Internally, a transverse groove extends laterally from this median foramen. The anterior arch possesses a prominent median tubercle and a large internal facet for the articulation of the odontoid process of the atlas. Externally, there is a faintly indented transverse line which demarcates the site of fusion. This line of fusion continues postero-laterally and circumscribes the union of the lateral masses to the condylar processes of the occipital bone.

The lateral masses are completely fused to the occiput. The inferior articulating surfaces are round to slightly reniform, have a flat to slightly convex configuration, and are directed in a posterior, medial and inferior fashion. Superior to the articular facets on the internal surfaces are "blind foramina" which undermine the facets.

The transverse processes are rudimentary. The costal elements are lacking, although there is a short projection of bone extending laterally from the lateral mass bilaterally. The transverse element lacks a distal segment, demonstrated by a rough, cancellous surface at its distal termination. Apparently the distal extremity was attached by a sutural joint which was not calcified. Because of the costal element deficiency, the foramina transversaria are incomplete at its anterior edge. The space between the transverse

processes and the occipital bone measures about 8 mm., showing no evidence of fusion between these structures.

The posterior arch is intact and free from fusion with the posterior rim of the foramen magnum. Posterior to the lateral masses bilaterally, the posterior arch is narrowed by the groove for the passage of the vertebral artery into the spinal canal. Posteriorly, the arch becomes thickened into a posterior median tubercle. The posterior atlanto-occipital space is decreased to 1.5 - 2.0 mm. The posterior rim of the foramen magnum projects downward, which tends to narrow this gap.

The hypoglossal canals and posterior condyloid foramina are of normal number, size and direction. However, the left jugular foramen is enormous, measuring 19 mm. by 13 mm. at its external port. The lateral anterior extent of the jugular foramen ends in a "blind" pouch or cul-de-sac. No other anomalous foramina are noted.

#### Skull 0-9

This skull bears multiple sites of fusion with the atlas. The atlas is asymmetrical as well as its fusion to the skull. The anterior arch is completely fused with the basi-occiput. It has a prominent anterior median tubercle externally and small facet for the articulation of the odontoid process of the axis internally. There is no anterior atlanto-occipital space or foramen. The inferior border of the arch is irregular and rugged, possessing a spur-like projection halfway between the median tubercle and the left inferior articulating surface. Internally, a transverse groove extends from one lateral mass to the other, superior to the facet for the odontoid process.

The lateral masses are thoroughly fused to condylar process of the occipital bone. Internally, the surface is quite rough and irregular,

although a transverse groove demarcates the line of fusion. The left inferior articulating surface is larger than the right. The left articulating surface is oval to reniform in shape, slightly concave in contour. The right facet is round and flat. The right inferior articulating surface extends further caudally than the left. Both articulating surfaces are directed medially and inferiorly.

The transverse processes are incompletely formed, both lacking costal elements. The left transverse element is well-formed and terminates in a well-developed distal extremity. The rudimentary costal element consists of a spur projecting laterally from the lateral mass. As a result, the groove in the transverse process for the vertebral artery is approximately seven-eighths circumscribed. Lateral to this groove, two vertical pillars are fused together, joining the transverse process with a paracondyloid process of the occipital bone. Consequently, an antero-posteriorly directed foramen is formed to convey the vertebral artery posteriorly. The right transverse process is less well-developed. The distal extremity is a small knobby projection which is directed slightly inferiorly. The groove in the transverse process for the vertebral artery is poorly developed, being only 50% circumscribed. No fusion exists between the right transverse process and the occipital bone; however, an elongated paramastoid process is extending from the posterior rim of the jugular foramen.

The posterior arch is incomplete, the gap measuring 3 mm. between the right and left sides. The left portion is free of fusion with the occipital bone. It is separated by about 2 mm. from the posterior rim of the foramen magnum. Its distal extremity extends beyond the posterior midline. On the superior surface of the posterior arch, near the left lateral mass, there is a groove for the passage of the vertebral artery into the spinal canal. The

right posterior arch segment is fused to the rim of the foramen magnum throughout its length, except for the posterior 3 mm. at its distal extremity. The line of fusion is well-delineated on the external surface. The fusion of the posterior arch with occipital rim, along with the fused lateral mass, creates a foramen for the vertebral artery to enter the spinal canal. Near this foramen, a small spicule of bone extends down from the occipital bone, lateral to the occipital-posterior arch fusion just mentioned, and fuses with an upward projection of the atlantal arch. This site of fusion produces a small foramen running tangentially to the primary site of fusion.

The hypoglossal canals, the left posterior condyloid foramen and the jugular foramina appear normal in size, shape and distribution. The right posterior condyloid foramen is absent. Anomalous foramina are not visualized.

#### Skull 0-10

This skull exhibits many of the features of assimilation of the atlas. The atlas is fused to the rim of the foramen magnum circumferentially in a symmetrical fashion. The atlas is so fused that the only points of non-fusion are three foramina communicating the spinal canal with extravertebral structures at the level of the atlanto-occipital fusion. These foramina are the anterior median atlanto-occipital foramen and the bilateral lateral atlanto-occipital foramen for the entrance of the vertebral artery, situated directly posterior to the lateral masses.

The anterior arch is well-developed and completely fused to the basiocciput except for the anterior median atlanto-occipital foramen, measuring approximately 2 mm. in diameter. There is a prominent median tubercle externally and a well-defined oval facet for the odontoid process of the axis internally. This facet measures 9 mm. in the transverse plane and 5 mm. in

the sagittal plane. Superior to this facet on the internal surface is a well-demarcated transverse groove passing through the internal orifice of the median foramen. This groove, terminating at the midpoint of the lateral masses bilaterally, indicates the line of fusion.

The fusion of the lateral masses is continuous with that of the anterior arch. The internal surface is roughened for the attachment of the transverse ligament. The right inferior articulating surface extends further caudally than the left. The inferior articulating surfaces are asymmetrical. The left facet is ovoid and flat and is directed in a medial and inferior direction. The right articulating surface is irregular in shape, having a basic rectangular configuration with a finger-like extension in a posterolateral direction. The facet is directed medially, posteriorly and inferiorly.

The transverse processes are completely formed, bearing properly fused transverse and costal elements. The foramina transversaria are intact. The left costal element is thin at its distal end. Bilaterally, a small sharp, pointed paracondyloid process descends to within 2 - 3 mm. from contacting the costal elements. The distal extremities exist as enlargements or knobs.

The posterior arch, although completely intact, is assimilated into the posterior rim of the foramen magnum, causing a downward, projecting ridge or lip at the foraminal orifice. At the junction with the lateral masses, this fusion is interrupted by the foramina conveying the vertebral arteries medially into the spinal canal.

On the left side, the hypoglossal canal is divided in two by a vertical spicule of bone at its internal orifice, which becomes singular externally. The right hypoglossal canal appears normal. In depressions, just lateral to the lateral atlanto-occipital foramen, are clusters of foramina

which are directed anteriorly into the jugular foramina, thus comprising posterior condyloid foramina. The jugular foramina are enlarged bilaterally, possessing "blind" dilated pouches in their antero-lateral two-thirds.

The skull is attached to the atlas in a symmetrical manner. However, since the right lateral mass projects a greater distance inferiorly, it is assumed that a slight inclination or tilt of the head to the left existed, when the head was held in a neutral position.

#### Skull 0-11

In contrast to Skull 0-10, this skull exhibits features of pure atlanto-occipital fusion. The atlas is completely formed and well-developed. The sole areas of fusion are located between the lateral masses of the atlas and the condylar components of the occipital bone.

The anterior arch is well-developed, bearing a prominent median tubercle externally and a well-defined articular facet for the odontoid process internally. The facet measures 9 mm. in the sagittal plane and 6 mm. in the transverse plane. A large kidney-shaped anterior atlanto-occipital space, measuring 6 mm. in the sagittal plane, extends from one lateral mass to the other. A rugged, broad projection extends superiorly from the midline of the anterior arch, causing some narrowing of the anterior atlanto-occipital space. This projection bears a portion of the facet for the odontoid process on its internal surface.

The lateral masses are thoroughly fused to the occipital condyles in the form of pillars. The internal and external surfaces are rough. The articular surfaces are symmetrically round, slightly concave and directed medially, inferiorly, and slightly posteriorly.

The transverse processes have well-formed costal and transverse elements, completely enclosed foramina transversaria, and strong club-like distal extremities. The transverse processes are separated from the occipital bone by about 10 mm. Paracondyloid projections from the occipital bone are absent.

The posterior arch is well-developed and complete. The superior surface adjacent to the lateral masses is grooved for the passage of the vertebral arteries. Posteriorly, the arch becomes quite thickened, measuring 14 mm. at its posterior midline. The superior surface at the midline has a small rough elevation. This median projection is at the level of the foramen magnum.

The hypoglossal canals, posterior condyloid foramina, and jugular foramina are of normal size, shape and inclination. There are no apparent anomalous foramina in the occipital region of this skull.

The skull is situated posteriorly on the atlas. In the sagittal plane, the posterior median surface of the posterior arch of the atlas is 5 mm. anterior to Opisthion. The same relationship exists between the posterior median surface of the anterior arch and Basion. The anterior-posterior dimension of the spinal outlet is not reduced significantly, however. This posterior orientation of the skull on the atlas causes insignificant alteration in head posture in the neutral position.

#### Skull 0-12

This skull portrays the characteristics of atlanto-occipital fusion. Besides fusion of the lateral masses to the condylar processes of the occipital bone, fusion of the right posterior arch to the rim of the foramen magnum and of the right half of the anterior arch to the basi-occiput also exists.

The anterior arch is well-developed, possessing a prominent median tubercle externally, and a well-demarcated facet for the articulation of the odontoid process of the axis internally. This facet is circular and measures 11 mm. in diameter. The anterior atlanto-occipital space is limited to the left side, extending from the midline to the left lateral mass. On the internal surface, this cleft continues as a groove to the right lateral mass.

The lateral masses are completely fused to the condylar components of the occipital bone. The right lateral mass extends further caudally than the right side. The left inferior articular surface is round and slightly concave, while the right facet is somewhat triangular in shape, with its apex pointed in a latero-posterior direction, and flat in contour. Both articulating surfaces are of similar size and project in a medial and inferior direction.

The transverse processes are well-formed, bearing complete, properly fused costal and transverse elements. Intact foramina transversaria are present bilaterally. The distal extremities are enlarged in a club-like fashion. Paramastoid processes descend from the posterior rim of the jugular foramina bilaterally, approaching contact with the distal extremities of the transverse processes. Those gaps measure approximately 2 mm.; the distances between the transverse processes and the basi-occiput in the region of the foramina transversaria are approximately 9 mm.

The posterior arch is incomplete, lacking approximately 2 mm. in the right posterior region. The left half is free from fusion with the rim of the foramen magnum. The arch is separated from the occipital bone by one mm. in its middle one-third. The arch becomes thinner in a cephalad-caudad direction as it approaches the left lateral mass, where there is a groove for the passage of the vertebral artery into the spinal canal. There is an

enlargement of the distal left arch, about 8 mm. from its terminal end, which appears to be a posterior median tubercle, although it is located approximately 6 mm. to the left of the midline of the skull. Due to the deficiency in formation of a complete arch, it is possible that the arch has sprung open, displacing the posterior median tubercle to the left of the cranial midline. The right arch is partially fused to the rim of the foramen magnum. The distal extremity is free of fusion in its terminal 7 mm. Adjacent to the right lateral mass, a lateral atlanto-occipital foramen is formed for the passage of the vertebral artery into the spinal canal. A thin veil of bone projects superiorly from the external edge of the proximal arch, continuing antero-laterally to arise from the posterior margin of the transverse process. This papryceous projection partially covers the entrance into the lateral atlanto-occipital foramen.

The hypoglossal canals and posterior condyloid foramina are of normal size, shape and inclination. Medial to the right paramastoid process, a superficial foramen, covered by a small spicule of bone, runs from the medial base of this process antero-medially to exit just medial to the jugular foramen on the external surface of the skull. A small "blind foramen" enters the internal surface of the right lateral mass, superior to the inferior articulating surface. The right jugular foramen is somewhat enlarged.

Due to the greater caudal projection of the right lateral mass, it appears that the head would be inclined to the left when held in a neutral position.

Skull O-13

This skull presents with some unusual findings. The atlas appears to be compressed in antero-posterior direction and expanded in the transverse direction. The areas of fusion are the anterior arch and the lateral masses.

The anterior arch is totally fused to the basi-occiput. A small anterior median atlanto-occipital foramen persists. There is a prominent median tubercle externally and a small, less well-defined facet for the articulation of the odontoid process of the axis internally. Bilateral depressions are noted on the internal surface near the junction with the lateral masses. These depressions appear to be at the site of fusion.

The lateral masses are completely fused to the condylar elements of the occipital bone. The lateral masses tend to flare laterally, creating the image of a very wide vertebral canal. The inferior articulating surfaces are greatly inclined, facing medially, slightly posteriorly and inferiorly. Their shapes are reniform; both facets are slightly convex.

The transverse processes have a bizarre appearance. The right transverse process is composed of a transverse element and a costal element, enclosing an oval foramen transversarium. The distal extremity is poorly formed. The left transverse process consists of a transverse element only. The costal element is completely lacking, thus preventing the formation of a foramen transversarium, although a large groove persists in the transverse element for the vertebral artery. The distal extremity is decreased in size, but bears a terminal knob. One of the striking features is that the transverse processes are twisted downward to assume an inferior orientation. The right distal extremity comes within 4 mm. of contacting the lateral edge of the right inferior articulating surface.

The posterior arch is incompletely formed. The gap, however, occurs in an unusual place. It is located 6 mm. from the origin of the left portion of the arch, just posterior to the groove where the vertebral artery passes into the spinal canal. The gap measures 2 mm. The right arch, then, is composed of the right portion plus a significant portion of the left. The right arch inscribes a tighter arc so that the distal extremity of the right arch is placed inside that of the left arch. The right arch is in contact with the rim of the foramen magnum, although there is not a calcified union. This contact occurs just posterior to the "foramen" for the passage of the vertebral artery into the spinal canal and extends for 10 mm. posteriorly. Near the distal extremity, the arch becomes close to the left lateral rim of the foramen magnum. The posterior rim of the foramen magnum is irregular, having a rugged appearance.

The left hypoglossal canal is divided into two small foramina at its internal orifice. A thin spicule divides it into an anterior-superior orifice and a posterior-inferior orifice. On the external surface, there is no evidence of this division. The right hypoglossal canal and the posterior condyloid foramina appear normal. Superior to the fusion of the anterior arch to the basi-occiput is a large median foramen, which originates on the internal surface of the basi-occiput and parallels the surface of the clivus in a rostral direction. The foramen exits the clivus at approximately half the distance between the anterior rim of the foramen magnum and dorsum sellae. There is a small "blind foramen" in the right lateral mass, just superior to the inferior articulating facet. The right jugular foramen also appears enlarged.

Due to the abnormal conformation of the atlas, the anterior and lateral aspects of atlas are located 3 - 5 mm. away from the rim of the foramen magnum in the transverse plane, while the posterior arch slightly impinges on the foraminal outlet.

#### Skull 0-17

This specimen exhibits multiple upper cervical spine abnormalities. Besides occipitalization of the atlas, atlanto-axial fusion and fusion of C<sub>3</sub> to the axis are present, resulting in a tortuous column of fused vertebrae protruding from the base of the skull. The assimilation of one aspect of this cervico-occipital complex into another and the abundance of exophytic bone formation mask, or obscure, many of the anatomical features and details of this specimen.

The anterior arch of the atlas is well-formed, but is not directly fused to the basi-occiput. It bears an anterior median tubercle on its external surface which projects caudally a short distance. A symmetrical oval anterior atlanto-occipital space is present, measuring 7 mm. in the sagittal plane and 16 mm. in the transverse plane. This space is partially occluded by the odontoid process of the axis which projects into the foramen magnum and fuses solidly with its anterior rim in the midline. In addition, the odontoid process is fused to the internal superior rim of the anterior arch of the atlas. On the internal median surface of the anterior arch, fine spicules of bone bridge a 3 mm. gap to fuse with the odontoid process.

The lateral masses of the atlas are fused extensively to the condylar components of the occipital bone and to the superior articulating surfaces of the axis. These sites of fusion are overlaid by vast deposits of exostotic bone. Ridges of osteophytes project antero-laterally as shelves from the

fused lateral masses to obstruct the outlet of the hypoglossal canal bilaterally and the medio-posterior edge of the left jugular foramen. On the postero-lateral surface of each lateral mass is a well-defined groove, located superior to the origin of the posterior arch of the atlas, which must have been related to the course of the vertebral arteries.

The transverse processes of the atlas are well-developed, bearing properly fused costal and transverse elements. The foramina transversaria of the atlas are round to slightly ovoid and are of adequate size. The club-like distal extremities are canted downward. A narrow bar fuses the tip of the distal extremity of the left atlantal transverse process to the diminutive distal extremity of the left axial transverse process, thus producing an antero-posterior foramen between these processes and the fused lateral masses. Paracondyloid processes from the occipital bone are absent. The distance between the transverse processes and the occipital bone is considerable, measuring 19 mm. bilaterally at the distal extremities.

The posterior arch of the atlas is completely formed and is fused only to the left postero-lateral aspect of the foramen magnum rim, spanning 9 mm. A teardrop-shaped lateral atlanto-occipital foramen is present on the left side, connecting with the groove on the lateral mass for the passage of the left vertebral artery. On the right side, a groove exists for passage of the contralateral structure. The posterior median portion of the arch is irregular and rugged in appearance and sends a 4 mm. projection cranialward, extending into the posterior cranial fossa. The margin of the foramen magnum is irregular, possessing a significant amount of "lipping" on the right postero-lateral aspect.

In a basilar view, the orientation of the atlas to the base of the skull is abnormal in three respects: (1) The atlas is displaced slightly

anteriorly on the base of the skull; (2) the atlas is rotated to the left on the occipital bone; and (3) the atlas is tipped in the sagittal plane, so that the posterior arch is in close proximity to the occiput and the anterior arch is a considerable distance from the basi-occiput. However, the orientation of the axis to the atlas is quite different. The axis is twisted to the right as related to the atlas. The axis is displaced posteriorly to such a degree that the body of the axis approaches contact with the posterior arch of the atlas. In addition, the axis is tilted in the sagittal plane in such a way that the body of the axis is buried inside the lumen of the atlas, while the spinous process of the axis is separated from the posterior arch of the atlas by 18 mm. Due to the posterior displacement of the axis in relation to the atlas and the abnormal rotation in the sagittal plane, the antero-posterior dimension across the vertebral canal of the atlas is greatly reduced, measuring only 8 mm. The orientation of the third cervical vertebra to the axis, although highly fused to the axis, is essentially normal.

Of the bones involved in this series of fusions, the axis is the most deformed. Normally, the odontoid process is situated at right angles to the horizontal plane of the axis. In this specimen, the odontoid process is inclined so far anteriorly that the horizontal plane of the axis and the odontoid process assume nearly a straight line. As previously stated, the odontoid process is fused to the anterior rim of the foramen magnum at its tip and to the anterior arch of the atlas along its anterior surface. In addition, small bony spicules bind the odontoid process to the confluent left lateral mass. The bodies of the axis and the third cervical vertebra are strongly fused, although a transverse cleft is noted on their internal surface, indicating the site of fusion. On the left side, the superior articulating surface of the axis fuses directly with the lateral mass of the atlas. On the

right side, however, the body and pedicle send out an anteriorly directed process to fuse with the lateral mass of the atlas.

The transverse process of both the axis and C<sub>3</sub> are diminutive, although they all bear transverse elements, costal elements and foramina transversaria. On the right side, the foramina of C<sub>2</sub> and C<sub>3</sub> are sitting one on top of the other. However, the foramen transversarium of the axis is situated 10 mm. posterior to that of the atlas, so that the course of the right vertebral artery must have been quite tortuous, assuming a series of right angle bends in this region. On the left side, the foramen transversarium of the axis is located somewhat lateral to that of C<sub>3</sub> and, in turn, the foramen of the atlas is situated further lateral to that of the axis. As a result, the course of the left vertebral artery is somewhat tortuous, turning gently to pass through the next foramen on its ascent into the skull. The distal extremities of C<sub>2</sub> and C<sub>3</sub> are poorly developed. They tend to project in an inferior direction. Except for the fusion between the left distal extremity of the atlas with that of the axis, there is no other manifestation of fusion between transverse processes of these three vertebrae.

The superior articulating surfaces of C<sub>3</sub> are fused to the inferior articulating surfaces of the axis. The pedicles between these vertebrae are not fused. The neural arches of C<sub>2</sub> and C<sub>3</sub> are fused together bilaterally at their postero-lateral extent. The spinous processes, although in close approximation, are not fused to one another. The spinous process of the axis has a bifid appearance, while that of C<sub>3</sub> projects posteriorly as a single club-shaped protuberance. Posterior to the fused articular joints, the fusion of the neural arches has produced bilateral foramina entering into the vertebral canal, the right foramen larger than the left one.

The inferior articulating surfaces of C<sub>3</sub> are reniform in shape, extending onto the transverse element of the transverse processes. In so doing, the articulating surfaces are quite "cupped", having both anterior and posterior caudally projecting rims. These articulating surfaces do not have a medial or lateral component or tilt. The inferior surface of the vertebral body is triangular in shape with its apex pointing anteriorly. The surface is concave in an antero-posterior direction.

The hypoglossal canals are partially obscured by the overhanging of the fused lateral masses; however, they appear to be normal in size, shape and course. The posterior condyloid foramina appear to be normal, as well as the left jugular foramen. The right jugular foramen seems to be enlarged. At the fusion of C<sub>2</sub> and C<sub>3</sub>, the presence of normal intervertebral foramina exists, located between the vertebral bodies and the fused articular joints.

The abnormal orientation of the skull to the fused upper cervical spine is created by the summation of the various deformities at each vertebral level. The head, when placed in a neutral position, would be tipped forward and inclined to the right, with a slight rotation to the left. Due to the severe tortuosity and the extensive reduction in antero-posterior dimension of the vertebral canal at the C<sub>1</sub> level, this individual must have had significant neurological impairment.

#### Skull 0-18

The atlanto-occipital complex of this skull shows a high degree of fusion. The atlas, which is well developed, is fused with the occiput at its anterior arch, lateral masses and portions of the posterior arch.

The well-developed anterior arch is fused completely to the basi-occiput, except for a very small median atlanto-occipital foramen. There is

a very well-formed median tubercle externally and a small, less well-defined facet for the articulation of the odontoid process of the axis internally at its inferior border. It measures approximately 5 mm. in diameter. The internal surface is rough and has small oval bilateral depressions adjacent to the internal orifice of the anterior atlanto-occipital foramen.

The lateral masses are fused thoroughly to the condylar processes of the occipital bone. The inferior articulating surfaces are elliptical to reniform in shape, bilaterally symmetrical, and flat to slightly convex in contour. They are directed medially and inferiorly.

The transverse processes are remarkably deficient. The costal elements are absent, although there is a small crest protruding from each lateral mass for its articulation. The transverse elements exist as short, blunt, knob-like projections from their origin on the posterior arch. The anterior surfaces of this element do not have a groove for the vertebral artery. The left transverse process is free from fusion. The right transverse process is fused to the occiput at its origin, in continuity with the fusion of the lateral mass. A right paracondyloid process extends downward in close apposition to the proximal site of fusion between the transverse process and the occipital bone. A gap of 2 mm. separates the paracondyloid process from contacting the right transverse process. These two processes, however, are not close enough together to prevent the vertebral artery from crossing over the transverse element in its usual manner. Both transverse processes are inclined in an inferior direction.

The posterior arch is well-formed and intact. It is fused to the rim of the foramen magnum at three different sites. Bilaterally, fusion occurs at the postero-lateral aspect for a distance of 12 mm. Fusion also occurs at the posterior midline, measuring approximately 8 mm. Between the lateral

masses and the postero-lateral sites of fusion, lateral atlanto-occipital foramina are quite evident. Their function, of course, is to provide a pathway for the entrance of the vertebral arteries into the spinal canal. Between the posterior median fusion and the postero-lateral fusion on the right side, an oval posterior atlanto-occipital foramen exists. On the left side, this foramen is reduced to nothing more than a fine cleft. On the posterior aspect of the posterior arch, the inferior surface becomes relatively flat, smooth and somewhat shiny. This may represent an articulating facet with the neural arch of the axis.

The hypoglossal canals and the posterior condyloid foramina appear to be normal in size, shape and inclination. However, a thin sheet of bone extends inferiorly from the postero-lateral margin of the left posterior condyloid foramen. The left jugular foramen is partitioned into a large postero-lateral compartment and a small antero-medial compartment by a spicule of bone arising near the margin of the carotid canal. The right jugular foramen is enlarged. There is a very small foramen located within the proximally fused right transverse process coursing in an antero-posterior direction, which terminates close to the right posterior condyloid foramen.

#### Adolescent Skulls

##### Skull 0-4

This skull exhibits fusion of the atlas to the occiput. The fusion involves the right lateral mass and part of the anterior arch.

The anterior arch is well-formed, possessing a prominent median tubercle anteriorly and a well-defined internal median facet for the articulation with the odontoid process of the axis. The facet is tear-drop shaped, with the pointed projection angled to the right and downward. It measures

6 mm. in the sagittal plane and 9 mm. in the transverse plane. The right side of the anterior arch is solidly fused to the basi-occiput. An anterior atlanto-occipital space extends from just right of the midline to the left lateral mass, preventing fusion of the anterior arch to the basi-occiput on the left side. This gap measures 4 mm. in the sagittal plane and 9 mm. in the transverse plane.

The right lateral mass is thoroughly fused to the condylar component of the occipital bone, continuous with the fusion of the right anterior arch with the basi-occiput. The left lateral mass is in tight contact with the left condylar component; however, calcification of the interphase has not occurred to any significant extent. The inferior articulating surfaces are oval to reniform in shape, the right larger than the left. Both are flat in contour and are inclined medially, inferiorly and slightly posteriorly. The right inferior articulating surface extends further caudally than the left one.

The transverse processes are formed incompletely. Both have incomplete formation of the costal elements, causing the foramina transversaria to be open at their antero-lateral aspect. A small projection, directed laterally from each lateral mass, is the only evidence of costal element formation. The transverse elements are well-developed. The right distal extremity is blunted at its tip, showing exposed medullary bone. The left distal extremity appears to have a flat facet at its tip. These observations possibly indicate that the tips of the distal extremities are not fused yet to the transverse element. Downward projections from the occipital bone, posterior to the jugular foramen bilaterally, are present as paracondyloid processes. The gap between the paracondyloid process and the distal tip of the transverse process measures 2 mm. on the right side; that on the left side measures 4 mm.

The posterior arch is formed completely and is free of fusion with the posterior rim of the foramen magnum. On the right side, 9 mm. posterior to the fused lateral mass, a tubercle from the posterior arch extends superiorly to within one mm. of the rim of the foramen magnum. This projection produces an almost complete lateral atlanto-occipital foramen for the passage of the right vertebral artery. On the left side, the posterior arch is significantly thinned, producing a groove for the left vertebral artery.

The hypoglossal canals, the jugular foramina, and the left posterior condyloid foramen appear normal in size, shape and inclination. The right posterior condyloid foramen is small externally at the base of the fused lateral mass. It enters the posterior cranial fossa slightly medial to the groove for the sigmoid sinus as two extremely small foramina, separated by a thin spicule of bone. No other anomalous foramina are evident.

The skull is situated posteriorly on the atlas, causing a discrepancy in the alignment of the neural lumen in the mid-sagittal plane. The discrepancy measures 5 mm. anteriorly and 7 mm. posteriorly. The skull is slightly displaced to the right, as related to the atlas, and rotated to left. The rotation is observed by the direction to which the tips of the transverse processes are pointed. The right transverse process points to the right mastoid process, while the left is directed to the anterior rim of the left external auditory meatus. Due to the combination of left rotation and right displacement of the skull on the atlas, the anterior midline of the base of the skull and median tubercle of the anterior arch of the atlas are in proper alignment. As a result of the cephalad-caudad length discrepancies of the lateral masses and the rotation of the skull on the atlas, the head would tend to be inclined to the left and rotated to the left, when placed in its neutral position.

Skull O-14

This skull exhibits atlanto-occipital fusion, primarily involving the lateral masses and the anterior arch. These fused structures display many unusual features.

The anterior arch is moderately well-developed and is fused completely to the basi-occiput. The anterior median tubercle is ill-defined. There is no evidence of an anterior atlanto-occipital foramen on the external surface. Internally, there are two small midline "blind foramina" which start at the approximate level of fusion, but course antero-superiorly into the clivus. On either side of these small foramina are deep grooves or furrows running approximately in a transverse plane. The left furrow is located superior to the right one and is much deeper. These furrows may represent the site of fusion between the anterior arch of the atlas and the basi-occiput. Inferior to the left furrow and adjacent to the anterior border of the left inferior articulating surface is a faint circular facet-like structure, which is located several millimeters to the left of the midline. This facet-like structure may represent the site of articulation with the odontoid process of the axis.

The lateral masses are fused extensively to the condylar components of the occipital bone. The previously mentioned furrows extend into the lateral masses internally. Projecting downward from the right lateral mass and the right half of the anterior arch, is a thick, broad mass of bone. The mass is 20 mm. wide in the horizontal plane, 16 mm. long in the superior-inferior direction, measuring from the furrow on the internal surface, and 4 mm. thick. At its postero-inferior extent, a small circular facet exists, whose plane is in an almost vertical direction. This facet measures approximately 8 mm. in diameter and is directed medio-posteriorly. This facet resembles the inferior

articulating surface seen on cervical vertebrae from C<sub>2</sub> to C<sub>7</sub>. This large bony mass may be a portion of the right pedicle and lateral mass from the axis fused to the lateral mass and anterior arch of the atlas, or it may be a portion of a persistent hypochordal arch of the axis which has fused to the atlas. The left inferior articular surface is reniform in shape and possesses a slight "lipping" at its anterior and medial extent. The facet is flat and is directed inferiorly and medially.

The transverse processes are formed incompletely, lacking complete costal elements bilaterally. The left transverse process has a well-developed transverse element with a thick club-shaped distal extremity. The costal element consists of a 7 mm. projection arising from the lateral mass, which fails to reach the transverse element by approximately 3 mm. Therefore, the left foramen transversarium is open on its antero-lateral extent. Descending from the occipital bone, posterior to the left jugular foramen, a paracondyloid process projects toward the distal end of the costal element; however, a gap of 3 mm. separates these structures. On the right side, the transverse element takes a downward bend soon after it arises from the junction of the lateral mass and posterior arch. It ends in an expanded distal knob, which lies at the same level as the inferior articulating surface on the greatly enlarged right lateral mass. On the posterior surface of the distal extremity, there appears to be a crescent-shaped concave depression, resembling an articulating facet. The right costal element is lacking, except for a minute spur located on the lateral mass. The groove on the anterior surface of the transverse element, related to the passage of the vertebral artery, is missing. However, superior to the origin of the transverse element, there is a well-demarcated groove, running horizontally on the base of the lateral mass, which may represent the course of the right vertebral artery.

The posterior arch is intact, but is extremely thin. It is fused to the rim of the foramen magnum at one point on its right postero-lateral aspect. The fusion is only observed when looking from the intra-cranial view. From the external view, a definite cleavage line exists. This point of fusion produces a right lateral atlanto-occipital foramen for the passage of the vertebral artery intra-cranially. At the left postero-lateral aspect, there is a thickening of the posterior arch which comes within one mm. of contacting the rim of the foramen magnum. The left proximal portion of the posterior arch becomes thinned and is grooved for the passage of the left vertebral artery.

The hypoglossal canals are normal in size, shape and inclination. The right posterior condyloid foramen appears normal externally, but its orifice within the posterior cranial fossa is located posterior to the groove for the sigmoid sinus. The left posterior condyloid foramen is missing, being represented by a pit just posterior to the fused lateral mass. The jugular foramina are of normal appearance externally. Within the posterior cranial fossa, however, thin sheets of bone arise from the petrous portion of the temporal bone, draping over and partially obstructing the internal orifices.

The orientation of the skull to the atlas is normal. However, due to the gross disparity in the lengths, or downward projections, of the lateral masses, the head would be inclined grossly to the left, when held in a neutral position.

#### Skull 0-15

This skull displays a well-developed atlas fused to the occipital bone at the lateral masses, anterior arch and the right posterior arch. The anterior arch is well-developed and is fused thoroughly to the basi-occiput. On

the internal surface, a well-defined transverse groove indicates the site of fusion. The articulating facet for the odontoid process of the axis is present in the midline, but poorly defined. A prominent median tubercle is observed externally. A typical anterior atlanto-occipital space or foramen is absent; however, an anomalous midline foramen courses through the anterior arch. Its external orifice is located in the center of the median tubercle and runs in a postero-superior direction to exit internally in the superior margin of the facet for the odontoid process, which is located several millimeters inferior to the transverse groove that demarcates the line of fusion. Laterally, on each side, a "blind" pouch or foramen appears superior to the anterior margin of the inferior articulating surfaces on its internal aspect.

The lateral masses are fused completely to the condylar components of the occipital bone. This fusion is in continuity with that of the anterior arch with the basi-occiput. Both lateral masses exhibit a similar degree of caudal projection. The inferior articulating surfaces are ovoid to reniform in shape and extend to a slight degree onto the anterior arch. These facets tend to extend onto the internal surface of the lateral masses for a short distance. The articulating surfaces are flat and are directed medially and inferiorly.

The transverse processes are formed incompletely. The transverse elements are well-developed, but lack a completely formed distal extremity. The underdeveloped costal elements fail to meet the transverse elements laterally, thus preventing the formation of intact foramina transversaria. The left foramen is opened antero-laterally by a gap measuring 2.5 mm., while the right one is open directly laterally by a one mm. gap. Small paracondyloid and paramastoid projections from the occipital bone are noted bilaterally, but are separated from the transverse processes by a considerable distance.

The right and left portions of the posterior arch, although well-developed, fail to meet at the posterior midline. The gap between the two halves is approximately 1.5 mm. The right half is fused to the rim of the foramen magnum throughout most of its course. The last four millimeters of the distal extremity are free of fusion. Just posterior to the right lateral mass, a large lateral atlanto-occipital foramen is present, to transport the right vertebral artery intra-cranially. The left half of the posterior arch is not fused to the occipital bone, although three small projections from the superior surface of the left posterior arch extend superiorly, which tends to contact similar downward projections from the rim of the foramen magnum. This event occurs approximately 8 mm. from its distal termination. The rim of the foramen magnum is irregular and ragged, having a tendency toward "lipping". The superior surface of the left arch is grooved for the passage of the left vertebral artery, located near the origin of the left posterior arch.

The hypoglossal canals, the posterior condyloid foramina and the jugular foramina are all normal in their size, shape, position and inclination. An accessory foramen is noted near the posterior midline in the occipital bone, approximately 8 mm. posterior to the margin of the foramen magnum. Its course is directed anteriorly into the posterior cranial fossa.

The skull appears to be situated slightly posterior on the atlas; otherwise, the orientation of the skull to the atlas seems to be proper. It appears that the head would have normal posture, when placed in a neutral position. The posterior projection of the occiput shows unilateral, or asymmetrical, bossing on the left side.

Skull O-16

This skull exhibits fusion between the atlas and occiput, involving the anterior arch and lateral masses. The posterior arch is missing, either as a result of fracture or failure of the main portion of the arch to be calcified onto its proximal elements. The occipital bone in this region is smooth and regular, suggesting that fusion did not exist posteriorly.

The anterior arch is moderately well-formed, but appears to be quite thin. It is fused completely to the basi-occiput. The site of fusion is demarcated by a transverse groove on the internal surface. A 2 mm. anterior median atlanto-occipital foramen enters into this groove. A median tubercle is prominent externally. The articulating facet for the odontoid process of the axis is defined poorly on its internal surface.

The lateral masses are fused thoroughly to the condylar processes of the occipital bone, except for their posterior extent. The posterior 4 - 5 mm. show spotty calcification of the atlanto-occipital joint. The fusion of the lateral masses is continuous with that of the anterior arch. Both lateral masses project caudally to the same degree. The inferior articulating surfaces are symmetrical, being reniform in shape, exhibiting a flat contour, and directed medially and inferiorly.

The transverse processes are poorly formed, having both deficient costal and transverse elements. Apparently, the distal extremities have not fused onto the transverse elements, since small articulating facets are present at their terminal ends. Rudimentary costal elements are observed projecting from the lateral masses bilaterally. The left costal element fails to meet the transverse element by 2 mm.; the gap on the right side measures 3 mm.

Both foramina transversaria are open antero-laterally. Paracondyloid processes project from the base of the skull, but they do not extend far enough to contact the transverse processes.

At the origins of the posterior arch, grooves are present for the passage of the vertebral artery into the spinal canal. As previously stated, the posterior arch is missing.

The hypoglossal canals and the right posterior condyloid foramen are normal in size, shape, position and inclination. The left posterior condyloid foramen is very small and is either incomplete or so small that it will not accept a probe. The left jugular foramen appears normal; the right is somewhat enlarged.

The orientation of the skull on the atlas appears normal. Therefore, a normal posturing of the head is assumed, when the head is placed in a neutral position.

## RESULTS

### Statistical Comparisons

Basic statistical analysis is performed on the cranial measurements used in the selection process to determine the normal skull population, or control group. Comparisons of cranial breadth, cranial length, and cranial index between Group A (occipitalized skulls) and Group B (normal skulls) demonstrate that there is no significant difference between the two groups. The cranial breadths of the 16 occipitalized and normal skulls are 12.97 cm.  $\pm$  0.58 cm. and 12.95 cm.  $\pm$  0.58 cm. respectively. The probability that they are from different populations, by the Students "T" Test, is 0.46. The cranial lengths of the 16 occipitalized and normal skulls are 17.31 cm.  $\pm$  0.98 cm. and 17.24 cm.  $\pm$  0.90 cm. respectively. The cranial length comparison between these two groups claims a probability of 0.42 that the groups are different. Comparing the cranial indices between the two groups of 16 skulls, 75.13  $\pm$  5.41 for occipitalized skulls and 75.15  $\pm$  5.21 for normal skulls, the probability that the groups are dissimilar is 0.50. Similar data are provided by comparing the 12 adult occipitalized and normal skulls and 4 adolescent occipitalized and normal skulls (Tables 2 and 3). The statistical evaluation by the Mann-Whitney "U" Test indicates there are no significant differences between these three cranial measurements of Groups A and B, regardless of sample size. Therefore, the two groups, based on cranial size data, are statistically within the same population.

Individual data points for each measurement on each skull, both occipitalized and normal, can be found in tables within the Appendix.

TABLE 2. CRANIAL MEASUREMENTS - BASIC STATISTICS

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
<u>Cranial Breadth (in cm.)</u>					
Occipitalized (A)	16	12.9688	$\pm 0.5851$	0.1511	0.0451
Normal (B)	16	12.9500	$\pm 0.5842$	0.1508	0.0451
Occipitalized (A)	12	13.0500	$\pm 0.6172$	0.1861	0.0473
Normal (B)	12	13.0250	$\pm 0.5879$	0.1773	0.0451
Occipitalized (A)	4	12.7250	$\pm 0.4573$	0.2640	0.0359
Normal (B)	4	12.7250	$\pm 0.5909$	0.3412	0.0464
<u>Cranial Length (in cm.)</u>					
Occipitalized (A)	16	17.3125	$\pm 0.9851$	0.2544	0.0569
Normal (B)	16	17.2438	$\pm 0.8996$	0.2323	0.0522
Occipitalized (A)	12	17.1750	$\pm 0.9459$	0.2852	0.0551
Normal (B)	12	17.1167	$\pm 0.8643$	0.2606	0.0505
Occipitalized (A)	4	17.7250	$\pm 1.1266$	0.6504	0.0636
Normal (B)	4	17.6250	$\pm 1.0243$	0.5914	0.0581

TABLE 2. CRANIAL MEASUREMENTS - BASIC STATISTICS (Continued)

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
<u>Cranial Index</u>					
Occipitalized (A)	16	75.1313	+ 5.4146	1.3980	0.0721
Normal (B)	16	75.1469	+ 5.2132	1.3460	0.0694
Occipitalized (A)	12	76.1875	+ 5.4344	1.6385	0.0713
Normal (B)	12	76.0958	+ 5.3170	1.6031	0.0699
Occipitalized (A)	4	71.9625	+ 4.5224	2.6110	0.0623
Normal (B)	4	72.3000	+ 4.2214	2.4372	0.0584

<sup>1</sup>Sample size of 16 indicates all skulls; 12 indicates adult skulls only; and 4 indicates adolescent skulls only.

TABLE 3. CRANIAL MEASUREMENTS - STATISTICAL ANALYSIS BETWEEN GROUPS A AND B

Measurement	Sample Size <sup>1</sup>	Students "T" Test		Mann-Whitney "U" Test	
		"T" Value	Probability	"U" Value	Probability <sup>2</sup>
Cranial Breadth	16	0.0907241	0.464157	123.5	n.s. <sup>3</sup>
Cranial Length	16	0.20615	0.419033	123.0	n.s.
Cranial Index	16	-0.00831526	0.496710	123.5	n.s.
Cranial Breadth	12	0.101612	0.459992	69.0	n.s.
Cranial Length	12	0.157709	0.438062	70.0	n.s.
Cranial Index	12	-0.0417702	0.483529	62.5	n.s.
Cranial Breadth	4	$5.1055 \times 10^{-6}$	0.499998	7.5	>0.448
Cranial Length	4	0.131358	0.449893	7.5	>0.448
Cranial Index	4	-0.109107	0.458337	6.5	0.343 < p < 0.448

<sup>1</sup>Sample size of 16 includes all skulls; 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>See Appendix for tables relating probability to "U" values per sample size. As the "U" value decreases, the probability value decreases, thus becoming more significant.

<sup>3</sup>n.s. indicates no statistical significance.

## CRANIAL BASE RELATIONSHIPS

The evaluation of the cranial base is separated into an assessment of measurements of the cranial base proper, including reference lines used in established cephalometric analyses, and an assessment of relationships which suggest evidence of basilar impression. The evaluation of the cranial base proper includes the basal angle (Nasion-Sella-Basion), the length from Sella to Nasion (anterior cranial fossa) and from Sella to Basion (posterior cranial fossa), the ratio between these two linear measurements, and the angular relationships between Frankfort Horizontal and the Nasion-Basion line and between Frankfort Horizontal and the Sella-Nasion line. The assessment of basilar impression related functions consists of linear measurements from Basion to reference lines, such as Chamberlain's Line (PNS-Op), the Mastoid Line, and the Digastric Line, and from the occipital condyle to the Digastric Line. Regarding occipitalized skulls, measurement points Derived Basion (DBa) and Pseudo-Basion (PBa) are substituted for Basion (Ba). Occipitalized skull 0-2 lacks an anterior arch of the atlas; therefore, data points involving Pseudo-Basion for this skull are not available. The data are analyzed for all 16 occipitalized skulls against their normal counterparts, for the 12 adult occipitalized skulls against their normal paired skulls, and for the 4 adolescent skull pairs.

### Cranial Base Proper

Statistical analysis involving the measurements of the cranial base proper indicates there is no statistical difference between the occipitalized skulls (Group A) and the normal skulls (Group B) in all three sets (16, 12, 4). The basal angle for the 16 occipitalized skulls is 131.7 degrees with a standard deviation of  $\pm 7.0$  degrees as compared to  $131.1^{\circ} \pm 5.3^{\circ}$  for the 16

normal skulls. The data for subsets of 12 and 4 show similar results (Tables 4 and 5). The distances from Sella to Nasion (S-N(mm)) and Sella to Basion (S-Ba(mm)) or Derived Basion (S-DBa(mm)) for the total 16 pairs are 67.5 mm.  $\pm$  5.5 mm. (Group A), compared to 68.2 mm.  $\pm$  4.3 mm. (Group B), and 42.75 mm.  $\pm$  4.7 mm. (Group A), as related to 44.5 mm.  $\pm$  2.8 mm. (Group B), respectively. In each instance, the means for the occipitalized skulls are slightly smaller in all three population sizes (16, 12, 4), although the differences are not statistically significant (Tables 6 and 7). The ratios of the S-Ba(S-DBa) length to the S-N length x 100 between the two groups of 16 skulls are 63.6  $\pm$  8.0 (Group A) and 65.4  $\pm$  4.0 (Group B). Note that the Group A values are smaller than the Group B values for the three population sizes, but again the differences are not statistically significant.

The evaluation of the basilar reference planes between Groups A and B indicates no statistical difference for the population size of 16 per group. However, considering the 12 adult skull populations only, the differences in values are close to being significant at the 0.05 confidence level. The relationship between Huxley's line (NBa or NDBa) and Frankfort Horizontal (FH), called the cranial deflection by Ricketts, reveals angles of 26.1°  $\pm$  3.9° (Group A) and 28.2°  $\pm$  2.3° (Group B) for the population size of 12 adult skulls (Table 8). The probability by the Students "T" Test is 0.062 (Table 9). Similarly, the measurement of the Sella-Nasion line (SN) in relation to FH reveals angles of 7.3°  $\pm$  3.3° (Group A) and 9.2°  $\pm$  2.8° (Group B) for the 12 adult skulls. The probability that these values are statistically different is 0.076 by the Students "T" Test. These differences may have some influence in those measurements where NBa(NDBa) and SN reference lines are used.

By substituting the point Pseudo-Basion (PBa) for Derived Basion (DBa) in measuring the basal angle (N-S-PBa) and the cranial deflection (NPBa-FH), statistically significant data are retrieved when compared with similar measurements on the normal skulls (N-S-Ba, NBa-FH) and DBa-containing measurements (N-S-DBa, NDBa-FH) on the occipitalized skulls. The probabilities are less than 0.001 by both the Students "T" Test and Mann-Whitney "U" Test, indicating that N-S-PBa (Group A) is statistically different from N-S-Ba (Group B) and N-S-DBa (Group A), and NPBa-FH (Group A) is statistically different from NBa-FH (Group B) and NDBa-FH (Group A), in both the 16 and 12 population sizes (Tables 4, 5, 8 and 9).

#### Basilar Impression Parameters

The assessments which tend to show evidence of basilar impression indicate a significant elevation of elements surrounding the foramen magnum among the occipitalized skulls. The relationship of Basion (or Derived Basion) to Chamberlain's Line (PNS-Op), the Mastoid Line and the Digastric Line are evaluated. The relationship of the most inferior aspect of the occipital condyle (OC) to the Digastric Line is assessed as well. The assessment related to PNS-Op is viewed in the mid-sagittal plane; the other three measurements are observed in the frontal plane.

For relationships involving PNS-Op and the Mastoid Line (ML), a positive value indicates that Ba, DBa or PBa is above that line; in other words, as the value increases, the more cephalad Ba, DBa, or PBa becomes. The distance DBa-PNSOp(mm) (Group A) is 5.8 mm.  $\pm$  3.5 mm. as compared to the Ba-PNSOp(mm) (Group B) value of 1.7 mm.  $\pm$  1.6 mm. for the 16 paired skull populations. The difference between these values is highly statistically significant at a less than 0.001 confidence level by both the Students "T"

Test and the Mann-Whitney "U" Test. The differences are about as significant in considering the 12 paired adult populations and the 4 paired adolescent skulls (Tables 10 and 11). For the populations of 16 paired skulls, the measurement DBa-ML(mm) (Group A) is 8.25 mm.  $\pm$  7.2 mm., as compared to 4.9 mm.  $\pm$  4.6 mm. for Ba-ML(mm) (Group B). The difference is not statistically significant, although close to being statistically significant by the Students "T" Test, with a probability of 0.065. Comparing the 12 paired adult skulls only, the values for DBa-ML(mm) (Group A) and Ba-ML(mm) (Group B) are 9.4 mm.  $\pm$  7.3 mm. and 3.8 mm.  $\pm$  4.2 mm. respectively. The difference between the two groups is statistically significant by both tests: the probability by the Students "T" Test is 0.016 and between 0.025 and 0.05 by the Mann-Whitney "U" Test (Tables 10 and 11). It is noted that the data values are reversed, when the 4 paired adolescent skulls are compared. The Group B (normal skulls) value is greater than the Group A (occipitalized skulls) value, although not statistically significant. The DBa-ML(mm) (Group A) measures 4.75 mm.  $\pm$  6.2 mm., compared to the Ba-ML(mm) value (Group B) of 8.25 mm.  $\pm$  4.8 mm. This aberration may be due to the small sample size.

For relationships involving the Digastric Line (DGL), a positive value indicates that Ba, DBa, PBa, OC are below this line; therefore, as the values decrease, the more cephalad Ba, DBa, PBa, and OC becomes. Considering all 16 paired skulls, the distance DBa-DGL(mm) (Group A) is 0.9 mm.  $\pm$  5.8 mm., as compared to 4.4 mm.  $\pm$  1.9 mm. for Ba-DGL(mm) (Group B). The difference is statistically significant by both tests; the probability is 0.014 by the Students "T" Test and between 0.025 and 0.05 by the Mann-Whitney "U" Test. The data are similar for the 12 paired adult skulls (Tables 12 and 13). The distance the inferior aspect of the occipital condyle is below the Digastric Line (OC-DGL(mm)) is 6.4 mm.  $\pm$  3.6 mm. for the occipitalized skulls (Group A)

and 13.5 mm.  $\pm$  2.8 mm. for the normal skulls (Group B), considering all 16 paired skulls. The difference between the two groups is highly statistically significant, with a confidence level less than 0.001 by both the Students "T" Test and the Mann-Whitney "U" Test. Similar data are obtained comparing the 12 paired adult skulls only (Tables 12 and 13).

The assessment of Pseudo-Basion (PBa), the inferior mid-sagittal point on the anterior arch of the atlas, in relation to the Mastoid Line (PBa-ML(mm)) and the Digastric Line (PBa-DGL(mm)) reveals that PBa is a distinctive point from DBa (occipitalized skulls) and Ba (normal skulls). The relationships of PBa-ML(mm) with DBa-ML(mm) (Group A) and Ba-ML(mm) (Group B), and PBa-DGL(mm) with DBa-DGL(mm) (Group A) and Ba-DGL(mm) (Group B), illustrate markedly significant statistical differences with probabilities less than 0.001 by both tests (Tables 10 - 13). These observations are particularly true for the analysis of the 16 paired skull populations. Evaluating PBa-ML(mm) against DBa-ML(mm) (Group A) and Ba-ML(mm) (Group B) for the 12 paired adult skull populations, a slightly less confidence level is observed.

The conclusions that can be drawn from the evaluation of the cranial base are: (1) there are no statistically significant differences between the groups regarding the cranial base proper; (2) there is a statistically significant elevation of the region surrounding the foramen magnum in occipitalized skulls; (3) there is a suggestion, though not statistically significant, that the reference planes, Nasion-Basion (Derived Basion) and Sella-Nasion, may be altered in occipitalized skulls; (4) Pseudo-Basion is a statistically significant, distinctive point in deference to Derived Basion and Basion.

TABLE 4. BASAL ANGLE - BASIC STATISTICS

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
N-S-DBa(A)	16	131.6875	+ 7.0116	1.8104	0.0532
N-S-Ba(B)	16	131.1250	+ 5.2773	1.3626	0.0402
N-S-PBa(A)	15 <sup>2</sup>	120.3333	+ 6.4771	1.7311	0.0538
N-S-DBa(A)	12	131.3333	+ 7.7381	2.331	0.0589
N-S-Ba(B)	12	131.0000	+ 5.9391	1.7907	0.0453
N-S-PBa(A)	11 <sup>2</sup>	119.6364	+ 6.1037	1.9304	0.0510
N-S-DBa(A)	4	132.7500	+ 4.9244	2.8431	0.0371
N-S-Ba(B)	4	131.5000	+ 3.1091	1.7951	0.0236
N-S-PBa(A)	4	122.2500	+ 8.0571	4.6518	0.0659

<sup>1</sup>Sample size of 15 or 16 indicates all skulls, 11 or 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>Excludes a value for occipitalized skull O-2, which is lacking the anterior arch of the atlas.

TABLE 5. BASAL ANGLE - STATISTICAL RELATIONSHIPS

Measurement (Group)	Sample Size <sup>1</sup>	Students "T"/Paired "T" Test		Mann-Whitney "U" Test	
		"T" Value	Probability	"U" Value	Probability <sup>2</sup>
N-S-DBa(A)	16	0.25639	0.3997	122	n.s. <sup>3</sup>
vs.	12	0.11838	0.453421	68.5	n.s.
N-S-Ba(B)	4	0.429273	0.341356	7	0.448
N-S-PBa(A)	15-16 <sup>4</sup>	-5.10046	0.0000	27	< 0.001
vs.	11-12	-4.52367	0.0000	14	< 0.001
N-S-Ba(B)	4	-2.14215	0.0379621	3.5	0.1 < p < 0.171
N-S-PBa(A)	15 <sup>5</sup>	12.9923	0.0000		
vs.	15-16			28	< 0.001
N-S-DBa(A)	11 <sup>5</sup>	11.2566	0.0000		
	11-12			15	< 0.001
	4	6.14817	0.00432807	3	0.1

<sup>1</sup>Sample size of 15 or 16 indicates all skulls; 11 or 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>See Appendix for tables of probability related to "U" values.

<sup>3</sup>n.s. indicates no statistical significance.

<sup>4</sup>Sample sizes 15-16 and 11-12 indicate exclusion of the value for occipitalized skull 0-2, which lacks the anterior arch of the atlas.

<sup>5</sup>Sample size 15 or 11 indicates exclusion of values for occipitalized skull 0-2 in the Students Paired "T" Test.

TABLE 6. BASILAR MEASUREMENTS - BASIC STATISTICS

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
S-N(mm) (A)	16	67.500	$\pm$ 5.5498	1.4329	0.0822
S-N(mm) (B)	16	68.1875	$\pm$ 4.3393	1.1204	0.0636
S-N(mm) (A)	12	67.9167	$\pm$ 6.0371	1.8203	0.0889
S-N(mm) (B)	12	68.0833	$\pm$ 3.3699	1.0161	0.0495
S-N(mm) (A)	4	66.2500	$\pm$ 4.1932	2.4210	0.0633
S-N(mm) (B)	4	68.5000	$\pm$ 7.2342	4.1767	0.1056
S-DBa (mm) (A)	16	42.7500	$\pm$ 4.7258	1.2202	0.1105
S-Ba (mm) (B)	16	44.5000	$\pm$ 2.8048	0.7242	0.0630
S-DBa (mm) (A)	12	43.2500	$\pm$ 5.1720	1.5594	0.1196
S-Ba (mm) (B)	12	44.4167	$\pm$ 2.6785	0.8076	0.0603
S-DBa (mm) (A)	4	41.2500	$\pm$ 3.0957	1.7873	0.0750
S-Ba (mm) (B)	4	44.7500	$\pm$ 3.5940	2.0750	0.0803
S-DBa:					
S-N x 100(A)	16	63.6125	$\pm$ 7.9947	2.0642	0.1257
S-Ba:					
S-N x 100(B)	16	65.3875	$\pm$ 3.9895	1.0301	0.0610

TABLE 6. BASILAR MEASUREMENTS - BASIC STATISTICS (Continued)

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
S-DBa:					
S-N x 100(A)	12	64.0167	$\pm$ 8.8530	2.6693	0.1383
S-Ba:					
S-N x 100(B)	12	65.3000	$\pm$ 3.6750	1.1080	0.0563
S-DBa:					
S-N x 100(A)	4	62.4000	$\pm$ 5.4394	3.1404	0.0872
S-Ba:					
S-N x 100(B)	4	65.6500	$\pm$ 5.4714	3.1589	0.0833

<sup>1</sup>Sample size of 16 indicates all skulls; 12 includes adult skulls only; 4 includes adolescent skulls only.

TABLE 7. BASILAR MEASUREMENTS - STATISTICAL RELATIONSHIPS

Measurement (Group)	Sample		Students "T" Test		Mann-Whitney "U" Test	
	Size <sup>1</sup>	"T" Value	Probability	"U" Value	Probability <sup>2</sup>	
S-N(mm) (A)	16	-0.390359	0.349515	121	n.s. <sup>3</sup>	
vs.	12	0.0835001	0.467104	69	n.s.	
S-N(mm) (B)	4	-0.538173	0.304913	6.5	0.343 < p < 0.448	
S-DBa (mm) (A)	16	-1.27378	0.106261	91.5	n.s.	
vs.	12	-0.693874	0.247512	58.5	n.s.	
S-Ba (mm) (B)	4	-1.47573	0.095235	4	0.171	
S-DBa: S-N x 100(A)	16	-0.794628	0.216536	96.5	n.s.	
vs.	12	-0.46378	0.323681	54.5	n.s.	
S-Ba: S-N x 100(B)	4	-0.842505	0.2159	6	0.343	

<sup>1</sup>Sample size of 16 indicates all skulls; 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>See Appendix for table of probabilities related to "U" values.

<sup>3</sup>n.s. indicates no statistical significance.

TABLE 8. BASILAR REFERENCE PLANES - BASIC STATISTICS

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
NDBa-FH(A)	16	26.7500	$\pm$ 3.8210	0.9866	0.1428
NBa-FH(B)	16	27.5000	$\pm$ 2.5820	0.6667	0.0939
NPBa-FH(A)	15 <sup>2</sup>	34.7333	$\pm$ 3.4323	0.9173	0.0988
NDBa-FH(A)	12	26.0833	$\pm$ 3.8954	1.1745	0.1493
NBa-FH(B)	12	28.1667	$\pm$ 2.2896	0.6904	0.0813
NPBa-FH(A)	11 <sup>2</sup>	34.5455	$\pm$ 3.9080	1.2358	0.1131
NDBa-FH(A)	4	28.7500	$\pm$ 3.2016	1.8484	0.1114
NBa-FH(B)	4	25.5000	$\pm$ 2.6458	1.5275	0.1038
NPBa-FH(A)	4	35.2500	$\pm$ 1.8930	1.0929	0.0537
SN-FH(A)	16	8.2500	$\pm$ 4.0249	1.0392	0.4879
SN-FH(B)	16	8.5625	$\pm$ 2.8277	0.7301	0.3302
SN-FH(A)	12	7.3333	$\pm$ 3.2845	0.9903	0.4479
SN-FH(B)	12	9.1667	$\pm$ 2.7579	0.8315	0.3009
SN-FH(A)	4	11.0000	$\pm$ 5.2915	3.0551	0.4810
SN-FH(B)	4	6.7500	$\pm$ 2.5000	1.4434	0.3704

<sup>1</sup>Sample size of 15 or 16 denotes inclusion of all skulls; 11 or 12 includes the adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>Excludes a value for occipitalized skull 0-2, which lacks the anterior arch of the atlas.

TABLE 9. BASILAR REFERENCE PLANES - STATISTICAL RELATIONSHIPS

Measurement (Group)	Sample Size <sup>1</sup>	Students "T"/Paired "T" Test		Mann-Whitney "U" Test	
		"T" Value	Probability	"U" Value	Probability <sup>2</sup>
NDBa-FH(A)	16	-0.650536	0.260149	112	n.s. <sup>3</sup>
vs.	12	-1.59719	0.0622438	46.5	n.s.
NBa-FH(B)	4	-1.56502	0.0843079	4	0.171
NPBa-FH(A)	15-16 <sup>4</sup>	6.65876	0.0000	7.5	< 0.001
vs.	11-12	4.82787	0.0000	7.5	< 0.001
NBa-FH(B)	4	5.99409	0.0000	0	0.014
NPBa-FH(A)	15 <sup>5</sup>	14.2404	0.0000		
vs.	15-16			15.5	< 0.001
NDBa-FH(A)	11 <sup>5</sup>	13.7358	0.0000		
	11-12			5.5	< 0.001
	4	5.46109	0.00603259	0	0.014
SN-FH(A)	16	-0.254121	0.400568	105.5	n.s.
vs.	12	-1.48079	0.0764208	43.5	n.s.
SN-FH(B)	4	1.45241	0.0982995	4.5	0.171 < p < 0.243

<sup>1</sup>Sample size of 15 or 16 denotes inclusion of all skulls; 11 or 12 includes the adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>See Appendix for probability tables related to "U" values.

<sup>3</sup>n.s. indicates no statistical significance.

<sup>4</sup>Sample sizes 15-16 and 11-12 indicate exclusion of the value for occipitalized skull 0-2, which lacks the anterior arch of the atlas.

<sup>5</sup>Sample size 15 or 11 indicates exclusion of values for occipitalized skull 0-2 in the Students Paired "T" Test.

TABLE 10. BASILAR IMPRESSION MEASUREMENTS I - BASIC STATISTICS

Measurement (in mm.) (Group)	Sample Size <sup>1</sup>	Mean <sup>2</sup>	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
DBa-PNSOp (A)	16	5.8125	+ 3.4683	0.8955	0.5967
Ba-PNSOp (B)	16	1.6875	+ 1.5798	0.4079	0.9362
DBa-PNSOp (A)	12	5.8333	+ 3.8573	1.1630	0.6613
Ba-PNSOp (B)	12	2.0000	+ 1.4771	0.4454	0.7385
DBa-PNSOp (A)	4	5.7500	+ 2.3629	1.3642	0.4109
Ba-PNSOp (B)	4	0.7500	+ 1.7078	0.9860	2.2771
DBa-ML (A)	16	8.2500	+ 7.1601	1.8487	0.8679
Ba-ML (B)	16	4.9375	+ 4.6256	1.1943	0.9368
PBa-ML (A)	15 <sup>3</sup>	-3.6667	+ 7.1780	1.9184	-1.9576
DBa-ML (A)	12	9.4167	+ 7.3045	2.2024	0.7757
Ba-ML (B)	12	3.8333	+ 4.1960	1.2651	1.0946
PBa-ML (A)	11 <sup>3</sup>	-3.3636	+ 7.5402	2.3844	-2.2417
DBa-ML (A)	4	4.7500	+ 6.2383	3.6017	1.3133
Ba-ML (B)	4	8.2500	+ 4.7871	2.7639	0.5803
PBa-ML (A)	4	-4.5000	+ 7.0475	4.0689	-1.5661

<sup>1</sup>Sample size of 15 or 16 indicates all skulls; 11 or 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>Positive values indicate that Ba, DBa or PBa is cephalad to the reference line; a negative value indicates these points lie caudad to the line.

<sup>3</sup>Excludes a value for occipitalized skull 0-2, which lacks an anterior arch of the atlas.

TABLE 11. BASILAR IMPRESSION MEASUREMENTS I - STATISTICAL RELATIONSHIPS

Measurement (in mm.) (Group)	Sample Size <sup>1</sup>	Students "T"/Paired "T" Test "T" Value	Probability	Mann-Whitney "U" Test "U" Value	Probability <sup>2</sup>
DBa-PNSOp(A)	16	4.32938	0.0000	40	< 0.001
vs.	12	3.21492	0.00199461	31	0.01
Ba-PNSOp(B)	4	3.42997	0.0069859	0	0.014
DBa-ML(A)	16	1.55439	0.0652889	100	n.s. <sup>3</sup>
vs.	12	2.29599	0.0157875	41	0.025 < p < 0.05
Ba-ML(B)	4	-0.890198	0.203817	4	0.171
PBa-ML(A)	15-16 <sup>4</sup>	-3.9934	0.0000	42	< 0.001
vs.	11-12	-2.86183	0.00466788	29	0.01 < p < 0.025
Ba-ML(B)	4	-2.9931	0.0121114	1.5	0.029 < p < 0.057
PBa-ML(A)	15 <sup>5</sup>	15.9385	0.0000		
vs.	15-16			38	< 0.001
DBa-ML(A)	11 <sup>5</sup>	14.4368	0.0000		
	11-12			18	0.001 < p < 0.01
	4	12.3333	0.000573933	3	0.1

<sup>1</sup>Sample size of 15 or 16 indicates all skulls; 11 or 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>See Appendix for tables of probability related to "U" values.

<sup>3</sup>n.s. indicates no statistical significance.

<sup>4</sup>Sample sizes 15-16 and 11-12 indicate exclusion of the value for occipitalized skull 0-2, which lacks the anterior arch of the atlas.

<sup>5</sup>Sample size 15 or 11 indicates exclusion of values for occipitalized skull 0-2 in the Students Paired "T" Test.

TABLE 12. BASILAR IMPRESSION MEASUREMENTS II - BASIC STATISTICS

Measurement (in mm.) (Group)	Sample Size <sup>1</sup>	Mean <sup>2</sup>	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
DBa-DGL(A)	16	0.9375	+ 5.7904	1.4951	6.1765
Ba-DGL(B)	16	4.4375	+ 1.8608	0.4805	0.4193
PBa-DGL(A)	15 <sup>3</sup>	12.2667	+ 6.8709	1.8363	0.5601
DBa-DGL(A)	12	0.5000	+ 5.4356	1.6389	10.8711
Ba-DGL(B)	12	4.8333	+ 1.7495	0.5275	0.3620
PBa-DGL(A)	11 <sup>3</sup>	12.4545	+ 6.6538	2.1041	0.5342
DBa-DGL(A)	4	2.2500	+ 7.5000	4.3301	3.3333
Ba-DGL(B)	4	3.2500	+ 1.8930	1.0929	0.5825
PBa-DGL(A)	4	11.7500	+ 8.5000	4.9075	0.7234
OC-DGL(A)	16	6.4375	+ 3.6142	0.9332	0.5614
OC-DGL(B)	16	13.5000	+ 2.7568	0.7118	0.2042
OC-DGL(A)	12	5.8333	+ 3.7376	1.1269	0.6407
OC-DGL(B)	12	14.4167	+ 1.8809	0.5671	0.1305
OC-DGL(A)	4	8.2500	+ 2.8733	1.6583	0.3482
OC-DGL(B)	4	10.7500	+ 3.4034	1.9650	0.3166

<sup>1</sup>Sample size of 15 or 16 indicates all skulls; 11 or 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>Positive values indicate that OC, Ba, DBa, or PBa is caudad to the reference line; when negative, these points lie cephalad to the line.

<sup>3</sup>Excludes a value for occipitalized skull 0-2, which lacks the anterior arch of the atlas.

TABLE 13. BASILAR IMPRESSION MEASUREMENTS II - STATISTICAL RELATIONSHIPS

Measurement (in mm.) (Group)	Sample Size <sup>1</sup>	Students "T"/Paired "T" Test		Mann-Whitney "U" Test	
		"T" Value	Probability	"U" Value	Probability <sup>2</sup>
DBa-DGL(A)	16	-2.30185	0.0142321	81.5	0.025 < p < 0.05
vs.	12	-2.62884	0.00766605	38	0.025 < p < 0.05
Ba-DGL(B)	4	-0.258556	0.402309	6.5	0.343 < p < 0.448
PBa-DGL(A)	15-16 <sup>3</sup>	4.39373	0.0000	32.5	< 0.001
vs.	11-12	3.83331	0.0000	14.5	< 0.001
Ba-DGL(B)	4	1.95218	0.0493804	4	0.171
PBa-DGL(A)	15 <sup>4</sup>	13.8255	0.0000		
vs.	15-16			25.5	< 0.001
DBa-DGL(A)	11 <sup>4</sup>	11.1359	0.0000		
	11-12			11	< 0.001
	4	14.7173	0.0000	3	0.1
OC-DGL(A)	16	-6.2148	0.0000	14.5	< 0.001
vs.	12	-7.10614	0.0000	1.5	< 0.001
OC-DGL(B)	4	-1.12272	0.152232	4.5	0.171 < p < 0.243

<sup>1</sup>Sample size of 15 or 16 indicates all skulls; 11 or 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>See Appendix for probability tables related to "U" values.

<sup>3</sup>Sample sizes 15-16 and 11-12 indicate exclusion of the value for occipitalized skull 0-2, which lacks the anterior arch of the atlas.

<sup>4</sup>Sample size 15 or 11 indicates exclusion of values for occipitalized skull 0-2 in the Students Paired "T" Test.

## FACIAL ANALYSIS

The assessment of facial skeletal form, therefore the result of facial growth, is evaluated by some of the parameters established by Ricketts and Steiner. Facial height parameters are those stated in the text by Hinds and Kent (1972). The Ricketts measurements assessed are the FH-NPo angle (facial angle or depth), the NBa(NDBa)-PtGn angle (facial axis), FH-GoGn angle (mandibular plane angle), and the linear distance pA-NPo(mm) (the convexity of the face). The Steiner parameters used are SNA (the anterior-posterior orientation of the maxilla to the cranial base), SNB (the anterior-posterior orientation of the mandible to the cranial base), ANB (the relationship of the maxilla to the mandible), and SN-GoGn (the mandibular plane angle). Additionally, the mandibular plane is related to the Nasion-Basion reference line (NBa(NDBa)-GoGn). The facial height assessment is evaluated by ratios of the measurements, Nasion-point A (N-pA) to point A - Pogonion (pA-Po) multiplied by 100, and Nasion-Anterior Nasal Spine (N-ANS) to Anterior Nasal Spine-Menton (ANS-Me) multiplied by 100.

### Ricketts Parameters

The facial depth assessment (FH-NPo) between Group A (occipitalized skulls) and Group B (normal skulls) reveals measurements of  $87.4^{\circ} \pm 3.9^{\circ}$  and  $90.25^{\circ} \pm 2.9^{\circ}$  respectively for the population size of 16 paired skulls. The difference between these two values is statistically significant by both tests; the probability by the Students "T" Test is 0.012 and between 0.01 and 0.025 by the Mann-Whitney "U" Test (Tables 14 and 15). Concerning the 12 paired adult skulls, the results are similar with confidence levels of 0.02 by the Students T" Test and between 0.025 and 0.05 by the Mann-Whitney "U" Test. The facial axis, represented by NDBa-PtGn (Group A) and NBa-PtGn

(Group B), measures  $88.8^{\circ} \pm 5.6^{\circ}$  and  $91.9^{\circ} \pm 3.8^{\circ}$  respectively for the population size of 16 skulls per group (Table 14). The difference is marginally significant, based on a 0.04 probability level by the Students "T" Test. The confidence level by the Mann-Whitney "U" Test is slightly greater than 0.05 (Table 15). The evaluation of the 12 paired adult skulls and the 4 paired adolescent skulls shows results that are not statistically significant. Using a Nasion-Pseudo-Basion (N-PBa) reference line, the data obtained are highly significant, comparing NPBa-PtGn (Group A) with NBa-PtGn (Group B) and NDBa-PtGn (Group A); the probabilities are less than 0.001.

The Ricketts mandibular plane angle (FH-GoGn) averages  $26.1^{\circ} \pm 8.7^{\circ}$  for Group A and  $21.4^{\circ} \pm 5.4^{\circ}$  for Group B, involving all 16 paired skulls. The difference reveals marginal statistical significance (Tables 16 and 17). The probability by the Students "T" Test is 0.051 and is slightly less than 0.05 by the Mann-Whitney "U" Test. For sample sizes of 12 and 4, no statistically significant differences are observed. The assessment of the convexity of point A (pA-NPo(mm)) reveals values of 5.1 mm.  $\pm$  2.8 mm. for Group A and 2.7 mm.  $\pm$  2.7 mm. for Group B, regarding the 16 paired skull populations. A positive value indicates that point A is anterior to the NPo line. The difference is statistically significant by both tests; the probability is 0.0085 by the Students "T" Test and between 0.01 and 0.025 by the Mann-Whitney "U" Test. Comparing the data for the 12 paired adult skulls, the results are similar, with the probabilities determined as 0.023 by the Students "T" Test and between 0.025 and 0.05 by the Mann-Whitney "U" Test (Tables 16 and 17).

#### Steiner Parameters

The review of the Steiner parameters reveals that differences between the two groups are not statistically significant for SNA, marginally

significant for SNB, and statistically significant for ANB (Tables 18 and 19). The values for SNA are  $84.6^{\circ} \pm 3.9^{\circ}$  (Group A) and  $84.7^{\circ} \pm 4.0^{\circ}$  (Group B) for the population size of 16 paired skulls. The difference is not statistically significant by both tests. Similar data for the 12 paired adult skulls are observed. The SNB values are  $78.5^{\circ} \pm 4.4^{\circ}$  (Group A) and  $80.4^{\circ} \pm 2.9^{\circ}$  (Group B), considering all 16 paired skulls. The difference is not statistically significant, but close to the confidence level of 0.05, noting a probability by the Students "T" Test of 0.075. The Mann-Whitney "U" Test indicates the difference to be insignificant. The evaluation of SNB for the 12 paired adult skulls reveals insignificant differences between the two groups. The assessment of ANB for the population sizes of 16 establishes means of  $6.1^{\circ} \pm 2.7^{\circ}$  and  $4.25^{\circ} \pm 2.7^{\circ}$  for Groups A and B respectively. A positive value indicates that line NA is anterior to the NB line; a negative value indicates the reverse is true. The difference between the two groups is statistically significant by both tests; the probability by the Students "T" Test is 0.028, and 0.05 by the Mann-Whitney "U" Test. Comparing the 12 paired adult skulls, the differences are insignificant, although marginally so by the Students "T" Test, showing a probability of 0.06.

The evaluation of the mandibular plane angle using two different reference lines, SN (Steiner) and NBa(NDBa), reveals data that are marginally significant (Tables 20 and 21). The SN-GoGn measurements depict values of  $34.3^{\circ} \pm 8.25^{\circ}$  for Group A and  $30.0^{\circ} \pm 6.055^{\circ}$  for Group B, analyzing the 16 paired skull populations. The probability that the data is statistically different is 0.51 by the Students "T" Test and slightly greater than 0.05 by the Mann-Whitney "U" Test. The difference in values for the 12 adult skull populations is statistically insignificant; however, the statistical analysis of the 4 adolescent skulls is again marginally significant. The means for

NDBa-GoGn (Group A) and NBa-GoGn (Group B) are  $52.9^{\circ} \pm 8.3^{\circ}$  and  $49.25^{\circ} \pm 5.9^{\circ}$  respectively for the 16 paired skull populations. The differences are marginally significant statistically. The probability by the Students "T" Test is 0.083, but insignificant by the Mann-Whitney "U" Test. For the 12 paired adult skulls, the differences in data are insignificant by both tests; however, the 4 adolescent skull data portends marginally significant differences.

Assessing the influence of Pseudo-Basion on the data, the PBa-containing measurements are proved to be significantly different from the DBa- and Ba-involved data. The value of  $58.9^{\circ} \pm 7.8^{\circ}$  for NPBa-GoGn (Group A) is significantly different from  $52.9^{\circ} \pm 8.3^{\circ}$  for NDBa-GoGn (Group A) and  $49.25^{\circ} \pm 5.9^{\circ}$  for NBa-GoGn (Group B) by both tests, considering the total skull population (see Table 21 for specifics). The results are similar, evaluating the data for the adult and adolescent populations individually.

#### Facial Height Parameters

The facial height analysis reveals no statistically significant differences between the two groups. The measurement Nasion to point A (N-pA(mm)) for Group A is  $54.25 \text{ mm.} \pm 5.7 \text{ mm.}$  as compared to  $52.4 \text{ mm.} \pm 4.2 \text{ mm.}$  for Group B, considering all 16 paired skulls. The difference is not statistically significant by either analytical method (Tables 22 and 23). The measurement point A to Pogonion (pA-Po(mm)) for Group A is  $51.1 \text{ mm.} \pm 5.3 \text{ mm.}$  as compared to  $51.25 \text{ mm.} \pm 5.9 \text{ mm.}$  for Group B. Again, the difference is not statistically significant by either test. The ratio of mid-facial height to lower facial height (N-pA:pA-Po x 100) computes to  $106.4 \pm 8.5$  for Group A (occipitalized skulls) and  $103.0 \pm 8.0$  for Group B (normal skulls). The difference in data between the two groups, once again, is statistically insignificant. Analyzing the values for the 12 paired adult skulls and 4 paired

adolescent skulls separately, the differences for N-pA(mm), pA-Po(mm) and N-pA:pA-Po x 100 between the two groups are also statistically insignificant.

Using the alternate facial height analysis, the results are the same (Tables 24 and 25). For the 16 paired skull populations, Nasion-Anterior Nasal Spine (N-ANS(mm)) measures 49.3 mm.  $\pm$  4.1 mm. for Group A and 48.1 mm.  $\pm$  3.8 mm. for Group B. The measurement Anterior Nasal Spine to Menton (ANS-Me(mm)) is 63.5 mm.  $\pm$  7.8 mm. for Group A and 63.3 mm.  $\pm$  6.9 mm. for Group B. The ratio N-ANS:ANS-Me x 100 is 78.2  $\pm$  6.5 for the occipitalized skulls (Group A) and 76.4  $\pm$  6.4 for the normal skulls (Group B). The differences for all parameters (N-ANS(mm), ANS-Me(mm), N-ANS:ANS-Me x 100) between the two groups are not statistically significant by either analytical method. The same can be said for the separate analysis of the 12 paired adult skull and the 4 paired adolescent skull populations.

TABLE 14. RICKETTS PARAMETERS I - BASIC STATISTICS

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
FH-NPo(A)	16	87.3750	+ 3.8794	1.0017	0.0444
FH-NPo(B)	16	90.2500	+ 2.8636	0.7394	0.0317
FH-NPo(A)	12	87.4167	+ 4.4202	1.3327	0.0506
FH-NPo(B)	12	90.6667	+ 2.6054	0.7855	0.0287
FH-NPo(A)	4	87.2500	+ 1.8930	1.0929	0.0217
FH-NPo(B)	4	89.0000	+ 3.6515	2.1082	0.0410
NDBa-PtGn(A)	16	88.8125	+ 5.6240	1.4521	0.0633
NBa-PtGn(B)	16	91.8750	+ 3.7925	0.9792	0.0413
NPBa-PtGn(A)	15 <sup>2</sup>	81.9333	+ 6.3411	1.6947	0.0774
NDBa-PtGn(A)	12	89.1667	+ 5.9823	1.8037	0.0671
NBa-PtGn(B)	12	91.3333	+ 3.3121	0.9986	0.0363
NPBa-PtGn(A)	11 <sup>2</sup>	82.0909	+ 7.3547	2.3257	0.0896
NDBa-PtGn(A)	4	87.7500	+ 4.9917	2.8819	0.0569
NBa-PtGn(B)	4	93.5000	+ 5.1962	3.0000	0.0556
NPBa-PtGn(A)	4	81.5000	+ 2.6458	1.5275	0.0325

<sup>1</sup>Sample size of 15 or 16 denotes inclusion of all skulls; 11 or 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>Excludes a value for occipitalized skull 0-2, which lacks the anterior arch of the atlas.

TABLE 15. RICKETTS PARAMETERS I - STATISTICAL RELATIONSHIPS

Measurement (Group)	Sample Size <sup>1</sup>	Students "T"/Paired "T" Test		Mann-Whitney "U" Test	
		"T" Value	Probability	"U" Value	Probability <sup>2</sup>
FH-NPo(A)	16	-2.38499	0.0117996	70.5	0.01 < p < 0.025
vs.	12	-2.1942	0.0195373	38.5	0.025 < p < 0.05
FH-NPo(B)	4	-0.850963	0.21372	5.5	0.243 < p < 0.343
NDBa-PtGn(A)	16	-1.80592	0.0404873	84	> 0.05 <sup>3</sup>
vs.	12	-1.09762	0.142121	54	n.s. <sup>4</sup>
NBa-PtGn(B)	4	-1.59604	0.0807958	4	0.100
NPBa-PtGn(A)	15-16 <sup>5</sup>	-5.33828	0.0000	14.5	< 0.001
vs.	11-12	-3.94482	0.0000	11	< 0.001
NBa-PtGn(B)	4	-4.11597	0.00312221	0	0.014
NPBa-PtGn(A)	15 <sup>6</sup>	12.7500	0.0000		
vs.	15-16			52.5	0.001 < p < 0.01
NDBa-PtGn(A)	11 <sup>6</sup>	11.6904	0.0000		
	11-12			31.5	0.01 < p < 0.025
	4	5.29009	0.00658894	2.5	0.057 < p < 0.100

<sup>1</sup>Sample size 15 or 16 indicates the inclusion of all skulls; 11 or 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>See Appendix for probability tables related to "U" values.

<sup>3</sup>Critical "U" value is 83 for p=0.05, sample size 16-16.

<sup>4</sup>n.s. indicates no statistical significance.

<sup>5</sup>Sample sizes 15-16 and 11-12 indicate exclusion of the value for occipitalized skull 0-2, which lacks the anterior arch of the atlas.

<sup>6</sup>Sample sizes 15 and 11 indicate exclusion of values for occipitalized skull 0-2 in the Students Paired "T" Test.

TABLE 16. RICKETTS PARAMETERS II - BASIC STATISTICS

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
FH-GoGn(A)	16	26.0625	+ 8.7061	2.2479	0.3340
FH-GoGn(B)	16	21.3750	+ 5.4145	1.3980	0.2533
FH-GoGn(A)	12	25.7500	+ 10.0826	3.0400	0.3916
FH-GoGn(B)	12	20.7500	+ 4.7314	1.4266	0.2280
FH-GoGn(A)	4	27.0000	+ 2.1602	1.2472	0.0800
FH-GoGn(B)	4	23.2500	+ 7.6322	4.4064	0.3283
pA-NPo (mm) (A)	16	5.1250 <sup>2</sup>	+ 2.7538	0.7110	0.5373
pA-NPo (mm) (B)	16	2.6875	+ 2.7011	0.6974	1.0051
pA-NPo (mm) (A)	12	5.4167	+ 3.1176	0.9400	0.5756
pA-NPo (mm) (B)	12	3.1667	+ 1.9924	0.6007	0.6292
pA-NPo (mm) (A)	4	4.2500	+ 0.9574	0.5528	0.2253
pA-NPo (mm) (B)	4	1.2500	+ 4.2720	2.4664	3.4176

<sup>1</sup>Sample size 16 indicates the inclusion of all skulls; 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>A positive value indicates that point A is anterior to the NPo line; a negative value, point A lies posterior to this line.

TABLE 17. RICKETTS PARAMETERS II - STATISTICAL RELATIONSHIPS

Measurement (Group)	Sample Size <sup>1</sup>	Students "T" Test		Mann-Whitney "U" Test	
		"T" Value	Probability	"U" Value	Probability <sup>2</sup>
FH-GoGn(A)	16	1.68533	0.05115	82.5	0.025 < p < 0.05
vs.	12	1.01633	0.16026	46.5	n.s. <sup>3</sup>
FH-GoGn(B)	4	1.64445	0.0755931	6.5	0.343 < p < 0.448
pA-NPo(mm) (A)	16	2.52764	0.00849253	72	0.01 < p < 0.025
vs.	12	2.1066	0.0233923	41.5	0.025 < p < 0.05
pA-NPo(mm) (B)	4	1.3705	0.109796	4.5	0.171 < p < 0.243

<sup>1</sup>Sample size 16 indicates inclusion of all skulls; 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>See Appendix for probability tables related to "U" values.

<sup>3</sup>n.s. indicates no statistical significance.

TABLE 18. STEINER PARAMETERS - BASIC STATISTICS

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
SNA(A)	16	84.6250	$\pm$ 3.8794	1.0017	0.0458
SNA(B)	16	84.6875	$\pm$ 4.0120	1.0359	0.0474
SNA(A)	12	85.9167	$\pm$ 2.2747	0.6858	0.0265
SNA(B)	12	84.9167	$\pm$ 3.7528	1.1315	0.0442
SNA(A)	4	80.7500	$\pm$ 5.4391	3.1402	0.0674
SNA(B)	4	84.0000	$\pm$ 5.2915	3.0551	0.0631
SNB(A)	16	78.5000	$\pm$ 4.3665	1.1274	0.0556
SNB(B)	16	80.4375	$\pm$ 2.9205	0.7541	0.0363
SNB(A)	12	79.4167	$\pm$ 3.7528	1.1315	0.0473
SNB(B)	12	80.0833	$\pm$ 2.8431	0.8572	0.0355
SNB(A)	4	75.7500	$\pm$ 5.5000	3.1754	0.0726
SNB(B)	4	81.5000	$\pm$ 3.3166	1.9149	0.0407

TABLE 18. STEINER PARAMETERS - BASIC STATISTICS (Continued)

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
ANB(A)	16	6.1250 <sup>2</sup>	$\pm$ 2.6802	0.6920	0.4376
ANB(B)	16	4.2500	$\pm$ 2.6708	0.6896	0.6284
ANB(A)	12	6.5000	$\pm$ 2.9388	0.8861	0.4521
ANB(B)	12	4.8333	$\pm$ 2.0375	0.6143	0.4216
ANB(A)	4	5.0000	$\pm$ 1.4142	0.8165	0.2828
ANB(B)	4	2.5000	$\pm$ 3.8730	2.2361	1.5492

<sup>1</sup>Sample size 16 indicates inclusion of all skulls; 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>A positive value for ANB exists when point A is anterior to point B; a negative value occurs when point A is posterior to point B.

TABLE 19. STEINER PARAMETERS - STATISTICAL RELATIONSHIPS

Measurement (Group)	Sample Size <sup>1</sup>	Students "T" Test		Mann-Whitney "U" Test	
		"T" Value	Probability	"U" Value	Probability <sup>2</sup>
SNA(A)	16	-0.0447961	0.482283	128	n.s. <sup>3</sup>
vs.	12	0.789367	0.219161	65.5	n.s.
SNA(B)	4	-0.856574	0.212282	6	0.343
SNB(A)	16	-1.4753	0.0752759	97	n.s.
vs.	12	-0.490493	0.314321	67	n.s.
SNB(B)	4	-1.179055	0.0617796	2.5	0.057 < p < 0.100
ANB(A)	16	1.98217	0.028343	83	0.05
vs.	12	1.61451	0.0603347	48	n.s.
ANB(B)	4	1.21268	0.135414	4.5	0.171 < p < 0.243

<sup>1</sup>Sample size 16 indicates inclusion of all skulls; 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>See Appendix for probability tables related to "U" values.

<sup>3</sup>n.s. indicates no statistical significance.

TABLE 20. STEINER AND OTHER PARAMETERS - BASIC STATISTICS

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
SN-GoGn(A)	16	34.3125	+ 8.2520	2.1307	0.2405
SN-GoGn(B)	16	30.0000	+ 6.0553	1.5635	0.2018
SN-GoGn(A)	12	33.0833	+ 8.8980	2.6828	0.2690
SN-GoGn(B)	12	30.0000	+ 5.5922	1.6861	0.1864
SN-GoGn(A)	4	38.0000	+ 5.0990	2.9439	0.1342
SN-GoGn(B)	4	30.0000	+ 8.2865	4.7842	0.2762
NDBa-GoGn(A)	16	52.8750	+ 8.3096	2.1455	0.1572
NBa-GoGn(B)	16	49.2500	+ 5.9161	1.5275	0.1201
NPBa-GoGn(A)	15 <sup>2</sup>	58.8667	+ 7.8182	2.0895	0.1328
NDBa-GoGn(A)	12	51.9167	+ 9.3367	2.8151	0.1798
NBa-GoGn(B)	12	49.3333	+ 5.4828	1.6531	0.1111
NPBa-GoGn(A)	11 <sup>2</sup>	57.6364	+ 8.8122	2.7867	0.1529
NDBa-GoGn(A)	4	55.7500	+ 3.3400	1.9076	0.0593
NBa-GoGn(B)	4	49.0000	+ 8.0416	4.6428	0.1641
NPBa-GoGn(A)	4	62.2500	+ 2.3629	1.3642	0.0380

<sup>1</sup>Sample size 15 or 16 indicates inclusion of all skulls; 11 or 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>Sample sizes 11 and 15 exclude the value for occipitalized skull 0-2, which lacks the anterior arch of the atlas.

TABLE 21. STEINER AND OTHER PARAMETERS - STATISTICAL RELATIONSHIPS

Measurement (Group)	Sample Size <sup>1</sup>	Students "T"/Paired "T" Test		Mann-Whitney "U" Test	
		"T" Value	Probability	"U" Value	Probability <sup>2</sup>
SN-GoGn(A)	16	1.68533	0.05115	87	>0.05 <sup>3</sup>
vs.	12	1.01633	0.16026	58	n.s. <sup>4</sup>
SN-GoGn(B)	4	1.64445	0.0755931	4	0.171
NDBa-GoGn(A)	16	1.4215	0.0827423	94	n.s.
vs.	12	0.826497	0.208698	62.5	n.s.
NBa-GoGn(B)	4	1.55282	0.0857278	4	0.171
NPBa-GoGn(A)	15-16 <sup>5</sup>	3.87787	0.0000	37.5	< 0.001
vs.	11-12	2.73938	0.00614291	27.5	0.001 < p < 0.01
NBa-GoGn(B)	4	3.16171	0.0097127	0	0.014
NPBa-GoGn(A)	15 <sup>6</sup>	14.372	0.0000		
vs.	15-16			68.5	0.01 < p < 0.025
NDBa-GoGn(A)	11 <sup>6</sup>	12.4395	0.0000		
	11-12			44	n.s.
	4	6.78903	0.00326639	0	0.014

<sup>1</sup>Sample size of 15 or 16 denotes inclusion of all skulls; 11 or 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>See Appendix for probability tables related to "U" values.

<sup>3</sup>Value close to being statistically significant. "U" value for sample size 16-16 is 83 at the 0.05 probability level.

<sup>4</sup>n.s. indicates no statistical significance.

TABLE 21. STEINER AND OTHER PARAMETERS - STATISTICAL RELATIONSHIPS (Continued)

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<sup>5</sup>Sample sizes 15-16 and 11-12 indicate the exclusion of the value for occipitalized skull 0-2, which lacks the anterior arch of the atlas.

<sup>6</sup>Sample sizes 15 and 11 indicate the exclusion of values for occipitalized skull 0-2 in the Students Paired "T" Test.

TABLE 22. FACIAL HEIGHT ANALYSIS I - BASIC STATISTICS

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
N-pA (mm) (A)	16	54.2500	$\pm$ 5.6627	1.4621	0.1044
N-pA (mm) (B)	16	52.4375	$\pm$ 4.2106	1.0872	0.0803
N-pA (mm) (A)	12	55.3333	$\pm$ 5.0692	1.5284	0.0916
N-pA (mm) (B)	12	53.0833	$\pm$ 3.9187	1.1815	0.0738
N-pA (mm) (A)	4	51.0000	$\pm$ 6.8799	3.9721	0.1349
N-pA (mm) (B)	4	50.5000	$\pm$ 5.0662	2.9250	0.1003
pA-Po (mm) (A)	16	51.0625	$\pm$ 5.2974	1.3678	0.1037
pA-Po (mm) (B)	16	51.2500	$\pm$ 5.9161	1.5275	0.1154
pA-Po (mm) (A)	12	52.2500	$\pm$ 5.5288	1.6670	0.1058
pA-Po (mm) (B)	12	51.0000	$\pm$ 4.7863	1.4431	0.0938
pA-Po (mm) (A)	4	47.5000	$\pm$ 2.3805	1.3744	0.0501
pA-Po (mm) (B)	4	52.0000	$\pm$ 9.4868	5.4772	0.1824

TABLE 22. FACIAL HEIGHT ANALYSIS I - BASIC STATISTICS (Continued)

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
N-pA:pA-Po x 100(A)	16	106.6125	$\pm$ 8.4984	2.1943	0.0797
N-pA:pA-Po x 100(B)	16	102.9750	$\pm$ 8.0313	2.0737	0.0780
N-pA:pA-Po x 100(A)	12	106.4083	$\pm$ 8.5319	2.5725	0.0802
N-pA:pA-Po x 100(B)	12	104.4417	$\pm$ 6.5903	1.9870	0.0631
N-pA:pA-Po x 100(A)	4	107.2250	$\pm$ 9.6714	5.5838	0.0902
N-pA:pA-Po x 100(B)	4	98.5750	$\pm$ 11.3509	6.5534	0.1151

<sup>1</sup>Sample size 16 indicates the inclusion of all skulls; 12 includes adult skulls only; 4 includes adolescent skulls only.

TABLE 23. FACIAL HEIGHT ANALYSIS I - STATISTICAL RELATIONSHIPS

Measurement (Group)	Sample Size <sup>1</sup>	Students "T" Test		Mann-Whitney "U" Test	
		"T" Value	Probability	"U" Value	Probability <sup>2</sup>
N-pA(mm) (A)	16	1.0274	0.156222	106	n.s. <sup>3</sup>
vs.	12	1.21647	0.118347	53.5	n.s.
N-pA(mm) (B)	4	0.117041	0.455323	7	0.448
pA-Po(mm) (A)	16	-0.094443	0.462692	120.5	n.s.
vs.	12	0.592129	0.279901	63	n.s.
pA-Po(mm) (B)	4	-0.920157	0.196491	5	0.243
N-pA:pA-Po					
x 100(A)	16	1.24435	0.111503	101.5	n.s.
vs.	12	0.631945	0.266967	61	n.s.
N-pA:pA-Po					
x 100(B)	4	1.16012	0.145036	4	0.171

<sup>1</sup>Sample size of 16 indicates inclusion of all skulls; 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>See Appendix for probability tables related to "U" values.

<sup>3</sup>n.s. indicates no statistical significance.

TABLE 24. FACIAL HEIGHT ANALYSIS II - BASIC STATISTICS

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
N-ANS (mm) (A)	16	49.3123	$\pm$ 4.1428	1.0697	0.0840
N-ANS (mm) (B)	16	48.0625	$\pm$ 3.7854	0.9774	0.0788
N-ANS (mm) (A)	12	50.2500	$\pm$ 3.9801	1.2000	0.0792
N-ANS (mm) (B)	12	48.4167	$\pm$ 3.7528	1.1315	0.0775
N-ANS (mm) (A)	4	46.5000	$\pm$ 3.6968	2.1344	0.0795
N-ANS (mm) (B)	4	47.0000	$\pm$ 4.2426	2.4495	0.0903
ANS-Me (mm) (A)	16	63.5000	$\pm$ 7.7632	2.0044	0.1223
ANS-Me (mm) (B)	16	63.3125	$\pm$ 6.9255	1.7882	0.1094
ANS-Me (mm) (A)	12	65.2500	$\pm$ 7.9444	2.3953	0.1218
ANS-Me (mm) (B)	12	63.4167	$\pm$ 5.5996	1.6884	0.0883
ANS-Me (mm) (A)	4	58.2500	$\pm$ 4.5735	2.6405	0.0785
ANS-Me (mm) (B)	4	63.0000	$\pm$ 11.1654	6.4464	0.1772

TABLE 24. FACIAL HEIGHT ANALYSIS II - BASIC STATISTICS (Continued)

Measurement (Group)	Sample Size <sup>1</sup>	Mean	Standard Deviation	Standard Error of the Mean	Coefficient of Variation
N-ANS:ANS-Me x 100(A)	16	78.1938	$\pm$ 6.5375	1.6880	0.0836
N-ANS:ANS-Me x 100(B)	16	76.3875	$\pm$ 6.4489	1.6651	0.0844
N-ANS:ANS-Me x 100(A)	12	77.6500	$\pm$ 7.5417	2.2739	0.0971
N-ANS:ANS-Me x 100(B)	12	76.6250	$\pm$ 6.0396	1.8210	0.0788
N-ANS:ANS-Me x 100(A)	4	79.8250	$\pm$ 0.6449	0.3723	0.0081
N-ANS:ANS-Me x 100(B)	4	75.6750	$\pm$ 8.5609	4.9426	0.1131

<sup>1</sup>Sample size 16 indicates the inclusion of all skulls; 12 includes adult skulls only; 4 includes adolescent skulls only.

TABLE 25. FACIAL HEIGHT ANALYSIS II - STATISTICAL RELATIONSHIPS

Measurement (Group)	Sample Size <sup>1</sup>	Students "T" Test		Mann-Whitney "U" Test	
		"T" Value	Probability	"U" Value	Probability <sup>2</sup>
N-ANS (mm) (A)	16	0.890988	0.190013	108	n.s. <sup>3</sup>
vs.	12	1.16097	0.129049	56.5	n.s.
N-ANS (mm) (B)	4	-0.177705	0.432401	7	0.448
ANS-Me (mm) (A)	16	0.0720923	0.471503	125	n.s.
vs.	12	0.653412	0.260131	61.5	n.s.
ANS-Me (mm) (B)	4	-0.78735	0.230519	5	0.243
N-ANS:ANS-Me					
x 100(A)	16	0.786789	0.218789	116	n.s.
vs.	12	0.367493	0.358381	70.5	n.s.
N-ANS:ANS-Me					
x 100(B)	4	0.966787	0.185494	6	0.343

<sup>1</sup>Sample size 16 indicates the inclusion of all skulls; 12 includes adult skulls only; 4 includes adolescent skulls only.

<sup>2</sup>See Appendix for probability tables related to "U" values.

<sup>3</sup>n.s. indicates no statistical significance.

### Correlation Analysis

Twenty-five measurements were selected from each group of 16 skulls, and their data points were entered into the multiple regression/correlation computer program entitled "MULREG". All measurements could not be used because of computer program limitations. The computer print-out provided a matrix of correlation coefficients comparing the statistical influence of each measurement on all the others. Due to the large size of these matrices, it is impossible to include the entire matrix within these pages; however, a portion of the correlation coefficient matrix for Group A (occipitalized skulls) is presented in Table 26. Two matrices were prepared, one for the 16 occipitalized skulls (Group A) and the other for the 16 normal skulls (Group B). (See Appendix for the statistical significance of the correlation coefficients.) A positive value for the correlation indicates that one measurement tends to vary directly with the other; whereas, a negative value indicates that the two measurements vary inversely to one another (as one measurement increases, the other decreases). Certain irrelevant correlations are not discussed in the text, such as the correlation between DBa-PNSOp(mm) and DBa-ML(mm), since they are measurements of the same function, the relationship of DBa to two different reference lines.

The measurement parameters were entered into the computer in a random order, not grouped together as related functions. Of course, data points from each skull were entered in the same order; i.e. in Group A, the data point from skull 0-1 was always first, followed by the data point from skull 0-2 which was always second, etc. (See the headings of the raw data tables in the Appendix for the order in which data points from each skull were entered into the computer.) The following measurements were selected for correlation

analysis, along with the corresponding numbers they were assigned in the computer program:

- 1 - N-S-DBa (Group A) or N-S-Ba (Group B)
- 2 - NDBa-FH (Group A) or NBa-FH (Group B)
- 3 - FH-NPo (Groups A and B)
- 4 - NDBa-PtGn (Group A) or NBa-PtGn (Group B)
- 5 - NDBa-GoGn (Group A) or NBa-GoGn (Group B)
- 6 - pA-NPo(mm) (Groups A and B)
- 7 - SNA (Groups A and B)
- 8 - SNB (Groups A and B)
- 9 - ANB (Groups A and B)
- 10 - SN-FH (Groups A and B)
- 11 - FH-GoGn (Groups A and B)
- 12 - DBa-ML(mm) (Group A) or Ba-ML.(mm) (Group B)
- 13 - N-pA(mm) (Groups A and B)
- 14 - pA-Po(mm) (Groups A and B)
- 15 - N-pA:pA-Po x 100 (Groups A and B)
- 16 - N-ANS(mm) (Groups A and B)
- 17 - ANS-Me(mm) (Groups A and B)
- 18 - N-ANS:ANS-Me x 100 (Groups A and B)
- 19 - S-DBa(mm) (Group A) or S-Ba(mm) (Group B)
- 20 - S-N(mm) (Groups A and B)
- 21 - S-DBa:S-N x 100 (Group A) or S-Ba:S-N x 100 (Group B)
- 22 - DBa-PNSOp(mm) (Group A) or Ba-PNSOp(mm) (Group B)
- 23 - OC-DGL (Groups A and B)
- 24 - Cranial breadth (cm) (Groups A and B)
- 25 - Cranial length (cm) (Groups A and B)

The correlation analysis is presented in related groups with one measurement declared as the dependent variable and the other measurements as independent variables. First, the measurements of the base of the skull which tend to suggest basilar impression (DBa-ML(mm) or Ba-ML(mm), DBa-PNSOp(mm) or Ba-PNSOp(mm), and OC-DGL(mm)) are correlated with the caliper-measured cranial breadth (CrB) and cranial length (CrL). Secondly, the measurements of the cranial base proper (S-DBa(mm) or S-Ba(mm), S-N(mm), S-DBa:S-N x 100 or S-Ba:S-N x 100, and N-S-DBa or N-S-Ba, the basal angle) are correlated with the cranial breadth and length of the skulls (CrB, CrL) and the basilar impression-related measurements stated above. Thirdly, the standard cephalometric reference lines (NDBa-FH or NBa-FH and SN-FH) are correlated with CrB, CrL, basilar impression-related measurements, and the measurements of the cranial base proper, as cited previously. Finally, the facial development parameters by Ricketts (FH-NPo, NDBa-PtGn or NBa-PtGn, pA-NPo(mm), and FH-GoGn), and by Steiner (SNA, SNB, ANB), as well as NDBa-GoGn and NBa-GoGn, and the facial height data are correlated with CrB, CrL, basilar impression-related measurements, the measurements of the cranial base proper, and the standard cephalometric reference lines. Noteworthy relationships among the facial parameters are addressed.

TABLE 26. CORRELATION COEFFICIENT MATRIX - EXAMPLE - GROUP A

$M_n$	1	2	3	4	5	25
1	0.999968	-2.30171E-02	0.33055	0.248625	-0.398897	7.23888E-03
2	-2.30171E-02	1.00000	0.357536	-0.50801	0.143827	0.257683
3	0.33055	0.357536	0.999948	0.571767	-0.70363	0.268956
4	0.248625	-0.50801	0.571767	1.00001	-0.789411	0.072577
5	-0.398897	0.143827	-0.70363	-0.789411	0.999996	-0.189592
↓	-----	-----	-----	-----	-----	-----
25	7.23888E-03	6.257683	0.268956	0.072577	-0.189592	0.999979

The above table is an example of a correlation coefficient matrix where the row and column headed by  $M_n$  indicate the measurements considered (from 1 - 25) and the numbers within the box indicate the correlation coefficients, i.e., the correlation coefficient of measurements 3 vs. 4 is 0.571767. Measurement data from all 16 occipitalized skulls are included.

## CRANIAL BASE RELATIONSHIPS

Basilar Impression Parameters

The correlation coefficients for the three basilar impression-related measurements, as related to the cranial breadth (CrB), indicate there is absolutely no correlation between these measurements and the cranial breadth in both Groups A and B. For Group B (normal skulls), there is a strong correlation between the three basilar impression-related measurements and the cranial length (CrL). The correlation coefficient between the distance Ba-ML(mm) and the cranial length (CrL) is 0.622329, with a probability slightly greater than 0.01 (Table 27). Noting that the Ba-ML(mm) distance is positive when Basion is above the Mastoid Line, then Basion becomes more cephalad in relation to the Mastoid Line when the cranial length increases, signified by a positive statistically significant correlation coefficient. In the normal skull population, the correlation coefficient between the distance Ba-PNSOp(mm), where a positive value indicates that Basion is above the PNSOp line (Chamberlain's Line), and the cranial length (CrL) is 0.681058, with a probability less than 0.01. Therefore, Basion becomes more cephalad in relation to the Posterior Nasal Spine-Opisthion line, when the cranial length increases.

The correlation coefficient between the OC-DGL(mm) distance, in which a positive value indicates that the inferior aspect of the occipital condyle (OC) is below the Digastric Line (DGL), and the cranial length (CrL) is -0.541676, possessing a probability of less than 0.05 (Table 27). Because of a negative statistically significant correlation coefficient, the occipital condyle's inferior aspect becomes more caudad in relation to the Digastric Line as the cranial length decreases; in other words, OC becomes more cephalad

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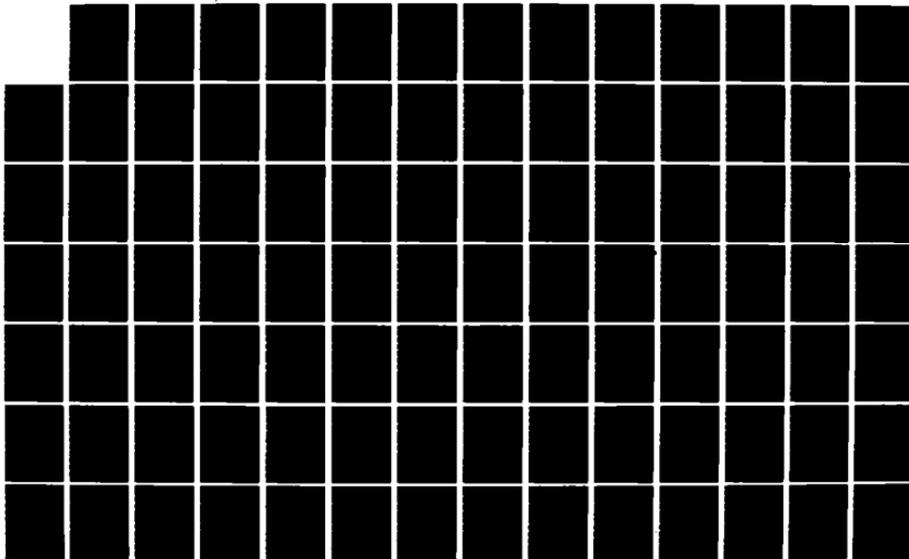
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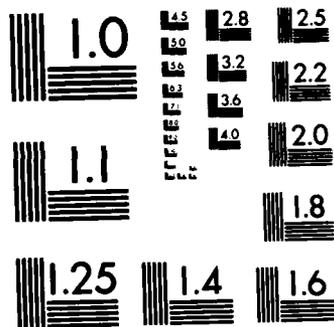
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in relation to the Digastric Line as the cranial length increases. Therefore, the basilar element becomes more cephalad in relation to the three reference lines as the cranial length increases for the normal skull population (Group B). Regarding the occipitalized skull population (Group A), the correlation coefficients of these three relationships to cranial length are statistically insignificant. This pattern suggests that the presence of occipitalization and its tendency toward basilar impression negates the influence of the cranial length on these measurements.

#### Cranial Base Parameters

The basal angle (N-S-DBa in Group A and N-S-Ba in Group B) shows no correlation with cranial length and breadth, DBa-ML(mm) or Ba-ML(mm), DBa-PNSOp(mm) or Ba-PNSOp(mm), and OC-DGL(mm) in either group. It does not even correlate statistically with the other measurements of the cranial base proper (S-DBa(mm) or S-Ba(mm), S-N(mm), and S-DBa:S-N x 100 or S-Ba:S-N x 100). The length of the clivus (S-Ba(mm)) correlates significantly with the cranial length in Group B (normal skulls), but not in Group A (occipitalized skulls). The correlation coefficient between S-Ba(mm) and the cranial length in Group B is 0.648631, a probability less than 0.01 (Table 27). It stands to reason that, as the skull gets larger in an anterior-posterior direction, other linear parameters measured in somewhat the same plane would increase also. The fact that S-DBa(mm) does not correlate significantly with the cranial length in occipitalized skulls (Group A) indicates that the presence of this skeletal anomaly alters the normal linear growth pattern in this region. The length of the clivus (S-DBa(mm) or S-Ba(mm)) is not correlated significantly with the cranial breadth in either group.

The relationship of S-Ba(mm) and the basilar impression-related measurements in Group B (normal skulls) is inconclusive. The length of the clivus does not correlate statistically with Ba-ML(mm) and OC-DGL(mm) in Group B; however, there is a statistically significant correlation between S-Ba(mm) and Ba-PNSOp(mm). The correlation coefficient between these two parameters is 0.534113, a probability less than 0.05 (Table 27). This relationship suggests that, as the point Ba becomes more cephalad in relation to the PNS-Op reference line, the length of the clivus increases. It can be inferred, as with other linear measurements, that as the size of the skull increases in an anterior-posterior direction, its parts will increase in size, as well as the distance between its parts, in a relatively proportional manner. Since point Op (Opisthion) of the PNS-Op reference line is located anatomically at the posterior rim of the foramen magnum in the mid-sagittal plane, opposite point Ba (Basion) on the anterior rim of the foramen magnum, there is a strong suggestion that the Basion and Opisthion have some influence on one another; therefore, the relationship between Basion and the PNS-Op line is not totally independent. Whereas Basion appears to be anatomically unrelated to the mastoid processes and the occipital condyle to the digastric grooves, the statistically insignificant correlations of Ba-ML(mm) and OC-DGL(mm) with the length of the clivus (S-Ba(mm)) seem to be of greater analytical importance. One must consider that the tips of the mastoid processes and the depths of the digastric grooves are not static in relation to the skull as a whole, but do vary from one skull to another. This notion gives further credence to the insignificant correlation coefficients of S-Ba(mm) with the Ba-ML(mm) and OC-DGL(mm) measurements in the normal skull population.

For the occipitalized skulls (Group A) the pattern is different, illustrating significant influences of the basilar impression-related parameters on the length of the clivus. The correlation coefficients of S-DBa(mm) with DBa-ML(mm), DBa-PNSOp(mm), and OC-DGL(mm) are -0.65411, -0.779916, and 0.65866 respectively. The probability values for the correlation coefficients between S-DBa(mm) and DBa-ML(mm) and between S-DBa(mm) and OC-DGL(mm) are less than 0.01, while the probability of the coefficient between S-DBa(mm) and DBa-PNSOp(mm) is less than 0.001 (Table 27). This data indicate that, as the Derived Basion (DBa) becomes more cephalad to the reference lines ML and PNSOp, the length of the clivus becomes shorter. As the occipital condyle's inferior aspect (OC) becomes more caudad from the reference line DGL, the length of the clivus (S-DBa(mm)) becomes greater, which in essence suggests the same conclusion as the other relationships (S-DBa(mm) related to DBa-ML(mm) and DBa-PNSOp(mm) respectively). It is quite obvious that the degree of basilar impression of the occipitalized skulls impacts greatly on the length of the clivus and tends to negate the influence of skull size, as manifested by the cranial length, on the development of the clivus.

The length of the anterior cranial floor (S-N(mm)) shows no statistical correlation with the cranial breadth (CrB) in either Group A or B. However, the measurement S-N(mm) is strongly correlated with the cranial length (CrL) in both groups, possessing correlation coefficients of 0.631583 for Group A (occipitalized skulls) and 0.737242 for Group B (normal skulls). The probability of both coefficients is less than 0.01, the probability of the correlation coefficient for Group B approaching 0.001 (Table 27). This relationship indicates that as the cranial length increases, so does the length of the anterior cranial floor. This relationship is somewhat tighter for the

normal skulls as compared to the occipitalized skulls, noting the difference in correlation coefficients of the two groups.

Regarding the normal skulls (Group B), the length S-N(mm) is somewhat influenced by the measurements, which tend to suggest basilar impression. The correlation coefficient between S-N(mm) and Ba-ML(mm) is 0.49882, possessing a probability of slightly less than 0.05 (Table 27). The correlation coefficient between S-N(mm) and Ba-PNSOp(mm) is 0.485638, having a probability that is slightly greater than 0.05. The correlation coefficient between S-N(mm) and OC-DGL is statistically insignificant (-0.409613), although the possibility of some correlation might exist. These relationships, once again, tend to infer that a certain distance or size of a cranial part is a direct result of total cranial longitudinal growth, which tends to proceed in an orderly fashion for normal skulls. For the occipitalized skulls (Group A), there are no significant correlations between the length of the anterior cranial floor (S-N(mm)) and the basilar impression-related measurements. Therefore, the presence of occipitalization of the atlas and the resultant tendency toward basilar impression does not influence or impact on the development of the anterior cranial floor.

The proportional relationship of the length of clivus to the length of the anterior cranial floor, expressed as the ratio  $S-Ba:S-N \times 100$ , shows no statistical correlation with the cranial breadth (CrB), the cranial length (CrL), or the basilar impression-related measurements for the normal skull population (Group B). Regarding the occipitalized skulls (Group A), this ratio is insignificantly correlated with the cranial breadth and length also. However, the ratio  $S-DBa:S-N \times 100$  is significantly correlated with the measurements related to basilar impression. The correlation coefficients of  $S-DBa:S-N \times 100$  with DBa-ML(mm), DBa-PNSOp(mm), and OC-DGL(mm) are -0.542881,

-0.610104, and 0.541298 respectively, all possessing probabilities of less than 0.05 (Table 27). This result is a direct effect of the influence of the basilar impression-related measurements on the length of the clivus (S-DBa(mm)) cited previously in occipitalized skulls. As DBa and OC become more cephalad in relation to their respective reference lines, the ratio becomes smaller, because the length of the clivus (the numerator in this ratio) decreases.

#### Basilar Reference Lines

Ricketts' angle of cranial deflection, NDBa-FH or NBa-FH, indicates no significant statistical correlation with the cranial breadth or length in either skull population. Since NDBa-FH and NBa-FH are angular measurements, it stands to reason that variations in size of linear measurements would have little impact on an angular measurement, as long as growth occurred proportionally. It is noted also that the angle of cranial deflection does not correlate significantly with the basal angle (N-S-DBa or N-S-Ba) in the normal or occipitalized skull populations. It can be theorized that minor adjustments in the lengths of the clivus and the anterior cranial floor and in the superior-inferior positioning of Sella can compensate for a more acute or obtuse basal angle, so that the orientation of the NDBa/NBa line remains unaltered in normal growth.

For normal skulls (Group B), the NBa line as related to the Frankfort Horizontal (NBa-FH) does not significantly correlate with the length of the clivus (S-Ba(mm)), the length of the anterior cranial floor (S-N(mm)) or the ratio involving these two measurements (S-Ba:S-N x 100). Once again, if growth occurs somewhat proportionally, the absolute linear relationships and their ratios have negligible influence on an angular measurement. Considering the occipitalized skull population (Group A), there are statistically

significant correlations between NDBa-FH and the length of the clivus (S-DBa(mm)) and between NDBa-FH and the ratio S-DBa:S-N x 100, but no significant correlation between NDBa-FH and S-N(mm). The correlation coefficients between NDBa-FH and S-DBa(mm) and between NDBa-FH and S-DBa:S-N x 100 are 0.553791 and 0.533257 respectively (Table 27). The probability of these coefficients is less than 0.05. These relationships tend to indicate that the decreasing length of the clivus, as the result of occipitalization and concomitant basilar impression, overrides the compensatory adjustments enough to reflect narrowing of the angle of cranial deflection. This pattern, in effect, indicates a mild disruption of the normal proportional growth cited previously.

It is interesting that the NBa-FH angle shows statistical correlation with Ba-ML(mm) and OC-DGL(mm), but absolutely no correlation with Ba-PNSOp(mm) within the normal skull population (Group B). The correlation coefficients between NBa-FH and Ba-ML(mm) and between NBa-FH and OC-DGL(mm) are -0.499586 and 0.515119 respectively (Table 27). The probabilities for these relationships are slightly less than 0.05. These relationships indicate that, as Ba and OC become more cephalad with respect to the reference lines, ML and DGL respectively, the angle NBa-FH becomes more acute. Since Basion is directly involved in both measurements (NBa-FH and Ba-ML(mm)), the effect of Basion will be felt on both measurements. Likewise, with the occipital condyles located adjacent to Basion along the rim of the foramen magnum, the influence of the occipital condyle (OC) is similar to that of Basion. Basion (Ba) is related somewhat to the reference line PNS-Op anatomically; therefore, as Basion moves, so does the line PNS-Op, thus eliminating any correlating effect on NBa-FH. As a result, a significant correlation does not exist between NBa-FH and Ba-PNSOp(mm) in the normal skull group.

Considering the occipitalized skulls (Group A), NDBa-FH is significantly correlated with all three basilar impression-related measurements. The correlation coefficients between NDBa-FH and DBa-ML(mm), DBa-PNSOp(mm) and OC-DGL(mm) are -0.645745, -0.572224 and 0.510505 respectively (Table 27). The probabilities are less than 0.01 for the correlation between NDBa-FH and DBa-ML(mm) and less than 0.05 for the correlations between NDBa-FH and DBa-PNSOp(mm) and OC-DGL(mm). The correlations involving DBa-ML(mm) and DBa-PNSOp(mm) are stronger within the occipitalized group than in the normal group, illustrating the increased impact caused by occipitalization and its allied anomalies. The effect of OC-DGL(mm) on NDBa-FH remains the same.

The relationship SN-FH is not correlated significantly with any of the cranial base relationships or basilar impression-related measurements in Group B (normal skulls). However, there are three relationships that are close to being significant, with probabilities slightly greater than 0.05. The correlation coefficients between SN-FH and CrL, S-Ba(mm) and N-S-Ba are -0.476809, -0.483335 and 0.486385 respectively (Table 27). As the skull increases in anterior-posterior dimension, the angle at which the Sella-Nasion line intersects with the Frankfort Horizontal tends to decrease, providing that the Sella-Nasion length increases with the cranial length and the superior-inferior orientation of Sella remains the same. With an increase in the length of the clivus, there is a tendency for the SN-FH angle to decrease. This observation is probably related to a superior positioning of Sella, when the length of S-Ba(mm) increases, thus producing a more acute SN-FH angle. Regarding the relationship of SN-FH with the basal angle (N-S-Ba), there is a tendency for the SN-FH angle to increase, when the basal angle increases. This phenomenon could be related to an inferior migration of Sella, when the basal angle increases, thus causing a steeper incline of the Sella-Nasion

line. This relationship is given further credence when analyzing occipitalized skulls. The correlation coefficient of SN-FH with N-S-DBa is 0.678559 in Group A skulls, possessing a confidence level of less than 0.01. Due to the considerable variation of the other cranial base parameters, no significant correlations between SN-FH and the other measurements are established among the occipitalized skulls.

TABLE 27. CORRELATION COEFFICIENTS - CRANIAL BASE

Dependent Variable	Independent Variable	Group A	Group B
<u>Basilar Impression</u>			
12 DBa(Ba)-ML(mm)	vs. 24 CrB	8.63455E-02	0.242984
	25 CrL	-0.306714	<u>0.622329</u>
22 DBa(Ba)-PNSOp(mm)	vs. 24 CrB	-0.124646	0.133624
	25 CrL	-9.68295E-02	<u>0.681058</u>
23 OC-DGL(mm)	vs. 24 CrB	4.15753E-02	-0.045492
	25 CrL	0.322297	<u>-0.541676</u>
<u>Basilar Measurements</u>			
19 S-DBa(Ba) (mm)	vs. 24 CrB	0.199547	0.122125
	25 CrL	0.315776	<u>0.648631</u>
	12 DBa(Ba)-ML(mm)	<u>-0.65411</u>	0.372551
	22 DBa(Ba)-PNSOp(mm)	<u>-0.779916</u>	<u>0.534113</u>
	23 OC-DGL(mm)	<u>0.65866</u>	-0.181061
20 S-N(mm)	vs. 24 CrB	-1.13094E-02	0.398438
	25 CrL	<u>0.631583</u>	<u>0.737242</u>
	12 DBa(Ba)-ML(mm)	-0.098985	<u>0.49882</u>
	22 DBa(Ba)-PNSOp(mm)	-0.164517	0.485638
	23 OC-DGL(mm)	6.14884E-02	-0.409613

TABLE 27. CORRELATION COEFFICIENTS - CRANIAL BASE (Continued)

Dependent Variable	Independent Variable	Group A	Group B
21 S-DBa(Ba):S-N x 100 vs.	24 CrB	0.182957	-0.286176
	25 CrL	-0.167876	-0.112688
	12 DBa(Ba)-ML(mm)	<u>-0.542881</u>	-0.133711
	22 DBa(Ba)-PNSOp(mm)	<u>-0.610104</u>	1.20366E-02
	23 OC-DGL(mm)	<u>0.541298</u>	0.246121
1 N-S-DBa(Ba) vs.	24 CrB	0.324154	0.283351
	25 CrL	7.23888E-03	-0.405801
	12 DBa(Ba)-ML(mm)	0.252634	-2.96995E-02
	22 DBa(Ba)-PNSOp(mm)	0.126274	-0.306849
	23 OC-DGL(mm)	-0.138934	9.16446E-02
<u>Basilar Reference Lines</u>			
2 NDBa(Ba)-FH vs.	24 CrB	0.264625	5.75699E-02
	25 CrL	0.257683	-0.345905
	12 DBa(Ba)-ML(mm)	<u>-0.645745</u>	<u>-0.499586</u>
	22 DBa(Ba)-PNSOp(mm)	<u>-0.572224</u>	2.45152E-02
	23 OC-DGL(mm)	<u>0.510505</u>	<u>0.515119</u>
	19 S-DBa(Ba)(mm)	<u>0.553791</u>	0.128879
	20 S-N(mm)	-2.20068E-02	-0.175533
	21 S-DBa(Ba):S-N x 100	<u>0.533257</u>	4.46968E-02
	1 N-S-DBa(Ba)	-2.30171E-02	-0.2593

TABLE 27. CORRELATION COEFFICIENTS - CRANIAL BASE (Continued)

Dependent Variable	Independent Variable	Group A	Group A
10 SN-FH	vs. 24 CrB	0.382922	0.312728
	25 CrL	0.300127	-0.476809
	12 DBa(Ba)-ML(mm)	-0.150365	-0.379406
	22 DBa(Ba)-PNSOp(mm)	-0.139688	-0.137109
	23 OC-DGL(mm)	0.161546	0.389118
	19 S-DBa(Ba)(mm)	0.12968	-0.483335
	20 S-N(mm)	0.107443	-0.155867
	21 S-DBa(Ba):S-N x 100	3.28366E-02	-0.330858
	1 N-S-DBa(Ba)	<u>0.678559</u>	0.486385

The number preceding each variable indicates the position of that variable within the correlation coefficient matrix.

The underlined correlation coefficients are statistically significant to at least the 0.05 confidence level.

See Appendix for critical values of the correlation coefficients.

## FACIAL RELATIONSHIPS

Ricketts Parameters

The relationships between FH-NPo (Ricketts' facial angle or depth) and the cranial/basilar parameters are somewhat intriguing. The angular measurement FH-NPo correlates significantly with the cranial length (CrL) and two basilar impression-related parameters (Ba-ML(mm) and OC-DGL(mm)) in Group B (normal skulls). It also has some tentative relationships, although not statistically significant, with Ba-PNSOp(mm) and the SN-FH angle among normal skulls. There is no apparent correlation between FH-NPo and the cranial breadth (CrB), NBa-FH or the measurements of the cranial base proper in this population. The correlation coefficients between FH-NPo and CrL, Ba-ML(mm), and OC-DGL(mm) are -0.560919, -0.562411 and 0.599545 respectively, all with probabilities less than 0.05 (Table 28). The coefficients of FH-NPo with Ba-PNSOp(mm) and SN-FH are -0.408908 and 0.434272 respectively.

The relationship between FH-NPo and the cranial length indicates that, as the cranial length increases, the mandibular mental protuberance becomes less protrusive, tending toward mandibular retrognathia. One interpretation is that the growth of the mandible or its forward orientation can not keep up with the increasing cranial length. Another explanation is that the increasing cranial length is partially manifested by an increased bossing of the glabella region, resulting in a further anterior positioning of Nasion, thus altering the orientation of the NPo line in relation to the Frankfort Horizontal. It is interesting to note that, in occipitalized skulls (Group A), the correlation coefficient between these two measurements is a positive value, although statistically insignificant, suggesting the reverse is true in that skull population.

The relationship between FH-NPo and the basilar impression-related measurements indicate that this angle decreases, as Basion and the occipital condyle become more cephalad in relation to their respective reference lines in normal skulls (Group B). The DBa-ML(mm) and DBa-PNSOp(mm) relationships with FH-NPo among occipitalized skulls tend to support this correlation, although their coefficients are not statistically significant. Considering the length of the clivus in this discussion, the relationships between FH-NPo and S-Ba(mm) and S-DBa(mm) are diametrically opposite of one another, although the correlation coefficients are not statistically significant. For normal skulls, the angle FH-NPo tends to decrease as S-Ba(mm) increases in length; whereas, there is an opposite tendency in occipitalized skulls. Relating FH-NPo with SN-FH in both populations, FH-NPo tends to increase as SN-FH increases. In most instances, an increased SN-FH angle indicates an inferior positioning of Sella, which may compensate for decreased lengths of the clivus in normal skulls. This downward thrust of Sella with related structures of the base of the skull tends to cause the mandible to be advanced forward. None of the cranial base parameters significantly correlates with FH-NPo in the occipitalized skulls.

Some of the other facial analysis measurements correlate or tend to correlate with FH-NPo. The angle of FH-NPo correlates significantly at the less than 0.05 confidence level with NDBa-PtGn (Group A) and NBa-PtGn (Group B), with correlation coefficients of 0.571767 and 0.506411 respectively (Table 29). As FH-NPo increases, so does NDBa-PtGn or NBa-PtGn. This is not surprising, since both tend to measure anterior-posterior orientation of the chin region. FH-NPo also correlates significantly with FH-GoGn in both groups, with correlation coefficients of -0.839611 (Group A) and -0.62987 (Group B). The statistical significance for Group A is less than 0.001 and

less than 0.01 for Group B. This relationship indicates that as FH-NPo increases, FH-GoGn decreases. This geometric phenomenon resembles the "triangle principle", because the relationship of these three lines differs from a triangle only by the distance between the points Gnathion and Pogonion, which are usually only 3 - 5 mm. apart in most instances. The "triangle principle" simply stated suggests that a change in one angle tends to affect the other angles of the same triangle inversely, since the sum of the three angles of the triangle must equal  $180^{\circ}$ . The relationship FH-NPo with NBa-GoGn in Group B (normal skulls) is close to being significant statistically, with a correlation coefficient of -0.487931 (probability just greater than 0.05), while FH-NPo correlates significantly with NDBa-GoGn in Group A (occipitalized skulls), possessing a coefficient of -0.70363 (probability less than 0.01). Since both FH-GoGn and NDBa-GoGn or NBa-GoGn are measurements of the mandibular plane angle, only using different reference lines, it is reasonable to assume that the relationship of NDBa-GoGn and NBa-GoGn with FH-NPo would be similar to that between FH-GoGn and FH-NPo.

Another relationship that shows some tendency toward statistical correlation is SNB related to FH-NPo. In normal skulls (Group B) the correlation coefficient is 0.464312, with a probability slightly greater than 0.05; however, the correlation coefficient in occipitalized skulls (Group A) is 0.50766, with a probability less than 0.05 (Table 29). This relationship is nothing more than two parameters measuring the same entity, i.e., the anterior-posterior position of the mandible as related to the cranial base. The reason this relationship is not more significant statistically is the result of the variability of the relationships between the SN reference line and the Frankfort Horizontal. There is also a tendency for correlation between FH-NPo and the mid-facial height in normal skulls, although there is

no significant correlation in occipitalized skulls. The correlation coefficients between FH-NPo and N-pA(mm) and N-ANS(mm) are  $-0.479621$  and  $-0.462773$  respectively; probabilities of both relationships are just greater than 0.05. These relationships indicate that as the height of the mid-face increases, the FH-NPo angle becomes smaller, or the mandible becomes smaller or more retrusive. This phenomenon correlates clinically with the "long face syndrome" due to excessive vertical growth of the maxillary alveolar processes.

Evaluation of the relationships involving NBa-PtGn, called the facial axis by Ricketts, and the cranial base parameters in the normal skull population indicates that only two relationships have any correlative tendencies, only one of which is statistically significant. NBa-PtGn (Group B) correlates significantly with the angle of cranial deflection (NBa-FH), with a correlation coefficient of  $-0.571885$ . The probability of this relationship is less than 0.05. This relationship is supported by the similar correlation of NDBa-PtGn with NDBa-FH in occipitalized skulls (Group A), in which the correlation coefficient is  $-0.50801$ , probability less than 0.05 (Table 28). This relationship indicates that NBa-PtGn or NDBa-PtGn angle decreases as the angle of cranial deflection increases. This relationship appears to have no influence on facial growth, but instead evaluates the effects produced by alterations in the orientation of the reference line (NBa or NDBa) on the measurement of the facial axis. In the normal skull population, there is a tentative relationship between NBa-PtGn and the basal angle (N-S-Ba), whereas this relationship in occipitalized skulls is lacking. The correlation coefficient between NBa-PtGn and N-S-Ba (Group B) is  $0.453836$ , with the probability somewhat greater than 0.05. This tendency suggests that the NBa-PtGn angle increases, as the basal angle increases. Again, this

relationship reflects some influence of one basilar measurement on a reference line, but little effect on facial form. Among the normal skull population, no other significant relationships or tendencies exist between NBa-PtGn and cranial breadth, cranial length, basilar impression-related measurements, length of the clivus, the length of the anterior cranial floor, the ratio of the two lengths, or the SN-FH angle. The same can be said for the occipitalized skull population, except for the relationship between NDBa-PtGn and the cranial breadth. The correlation coefficient between NDBa-PtGn and CrB is  $-0.565132$ , a probability value less than 0.05. This relationship suggests that the NDBa-PtGn angle increases as the width of the cranium becomes more narrow. This relationship is not born out statistically in the normal skulls, bearing a correlation coefficient of  $-0.330836$  (Table 28).

There are some statistically significant correlations between NDBa-PtGn (NBa-PtGn) and other facial parameters (Table 29). The relationship between FH-NPo and NDBa-PtGn (NBa-PtGn) has been discussed previously. The NDBa-PtGn (NBa-PtGn) angle correlates significantly with NDBa-GoGn (NBa-GoGn), FH-GoGn, SNB, and the mid-facial height parameters N-pA(mm) and N-ANS(mm) in both skull populations. The correlation coefficients between NDBa-PtGn and NDBa-GoGn (Group A) and between NBa-PtGn and NBa-GoGn (Group B) are  $-0.789411$  and  $0.723522$  respectively. The probabilities of these coefficients hover around the 0.001 confidence level. These measurements, using the same reference line, create the "triangle principle", as previously cited. The angles NDBa-PtGn and NBa-PtGn increase, as the angles NDBa-GoGn and NBa-GoGn decrease, indicating the chin becomes more protrusive, as the mandibular plane flattens. In addition, NDBa-PtGn and NBa-PtGn correlate with the mandibular plane angle as defined by FH-GoGn, although with a decreased confidence level of less than 0.05. The correlation coefficients of this relationship are

-0.583863 (Group A) and -0.500789 (Group B). Since the mandibular plane angles NDBa-GoGn (NBa-GoGn) and FH-GoGn differ only by the reference lines used, which are somewhat independent, then it stands to reason that similar relationships may exist between NDBa-PtGn (NBa-PtGn) and FH-GoGn, as occur between NDBa-PtGn (NBa-PtGn) and NDBa-GoGn (NBa-GoGn).

A significant correlation exists between NDBa-PtGn (NBa-PtGn) and SNB in both groups. The correlation coefficients in Groups A and B are 0.704463 and 0.619213 respectively (Table 29). The probability for Group A is less than 0.01 and the probability for Group B is slightly greater than 0.01. As the angle NDBa-PtGn (NBa-PtGn) increases, so does the angle SNB. This is not surprising, since both measurements indicate the anterior-posterior growth of the mandible, although NDBa-PtGn (NBa-PtGn) also involves the downward growth, or positioning, of the mandible as well.

The mid-facial height also impacts on the angle NDBa-PtGn (NBa-PtGn) statistically in both the occipitalized and normal skull populations. The correlation coefficients between NDBa-PtGn (NBa-PtGn) and N-pA(mm) are -0.546883 and -0.660154 for Groups A and B respectively, while the coefficients between NDBa-PtGn (NBa-PtGn) and N-ANS(mm) are -0.529534 and -0.524173 for Groups A and B respectively (Table 29). The probability of NBa-PtGn as related to N-pA(mm) in Group B is less than 0.01, whereas the probabilities of the other three relationships are less than 0.05. These relationships indicate the NDBa-PtGn (NBa-PtGn) angle increases, when the mid-facial height decreases; therefore, the orientation of the mandible becomes protrusive and elevated as the mid-face shortens, and vice versa. This relationship gains more weight, when it is realized that the relationships of NDBa-PtGn (NBa-PtGn) with the lower facial height measurements show a lack of correlation statistically. The only relationship that is close to being

statistically significant is the relationship between NBa-PtGn and ANS-Me(mm) for Group B only, with a correlation coefficient of  $-0.478143$ . The relationships between NDBa-PtGn (NBa-PtGn) and pA-Po(mm) in both groups are not statistically significant. Therefore, it appears that the angle NDBa-PtGn (NBa-PtGn) is influenced more by the mid-facial height than the lower facial height.

Another significant correlation exists between NDBa-PtGn and SNA in occipitalized skulls only. The correlation coefficient between these two angular measurements is  $0.5863$  in Group A, with a probability of less than  $0.05$ , but statistically insignificant in Group B, with a correlation coefficient of  $0.181288$  (Table 29). In occipitalized skulls, the anterior-posterior orientation of the maxilla (SNA) correlates with the anterior-posterior and superior-inferior orientations of the mandible (NDBa-PtGn). In the normal skull population, these orientations appear to occur independently.

None of the relationships involving pA-NPo(mm), Ricketts' measurement of facial convexity, and the cranial base parameters are statistically significant in either group of skulls. The only relationships that are close to being statistically significant are pA-NPo(mm) with S-Ba(mm) (the length of the clivus) in the normal skull population, with a correlation coefficient of  $0.444392$ , and pA-NPo(mm) with CrB (cranial breadth) in the occipitalized skull population, with a correlation coefficient of  $0.453648$  (Table 28). In either relationship the corresponding correlation coefficient in the other group shows absolutely no correlation, with values approaching zero. No apparent reasons can be deduced from these relationships, other than to say that pA-NPo(mm) tends to correlate directly with the length of the clivus in normal skulls and with the cranial breadth in occipitalized skulls.

Relationships between pA-NPo(mm) and other facial parameters show some statistically significant correlations. The measurement pA-NPo(mm) has an extremely high correlation with ANB, having correlation coefficients of 0.955204 for Group A and 0.963387 for Group B, the probabilities of which are far less than 0.001 (Table 29). The strong correlation is expected, since both measurements evaluate the same relationship, by different means. They both measure the relationship between maxilla and mandible in an anterior-posterior direction. It must be remembered that pA-NPo(mm) and ANB have positive values, when point A is anterior to the NPo line and when the line NA is anterior to line NB respectively.

The measurement pA-NPo(mm) correlates significantly with Steiner's SNA angle in the normal skull population, but shows absolutely no correlation in occipitalized skulls. The correlation coefficient between pA-NPo(mm) and SNA for Group B is 0.654803, possessing a probability less than 0.01 (Table 29). This relationship indicates that pA-NPo(mm) varies directly with SNA in normal skulls, both relating the anterior-posterior orientation of the maxilla. Regarding occipitalized skulls, the NPo line, Pogonion in particular, varies so greatly that a significant correlation between pA-NPo(mm) and SNA can not be computed. On the other hand, pA-NPo(mm) correlates significantly with SNB in occipitalized skulls, but not in normal skulls. The correlation coefficient between pA-NPo(mm) and SNB in Group A is -0.554413, with a probability of less than 0.05. This relationship indicates that the pA-NPo(mm) measurement varies inversely with SNB in occipitalized skulls, meaning that the maxilla becomes more protrusive in relation to the chin, as the mandible becomes retrusive. This phenomenon suggests that the maxilla remains relatively static in its position, while the NPo line and SNB angle vary in occipitalized skulls. However, in normal skulls, points A, B and Po tend to

move in concert with one another in a coordinated fashion, thus negating any significant relationship between these two measurements.

The relationship between pA-NPo(mm) and FH-NPo is somewhat marginal among occipitalized skulls, but absolutely insignificant among the normal skulls. The correlation coefficients are -0.46656 (Group A) and -0.040938 (Group B). These relationships tend to support the theory presented previously, discussing the relationships between pA-NPo(mm) and SNB. The measurement pA-NPo(mm) significantly correlates with the lower facial height, as defined by pA-Po(mm), in Group A and has a tendency to correlate with the lower facial height, defined by ANS-Me(mm), in Group A as well. These relationships do not correlate significantly in Group B. The correlation coefficients between pA-NPo(mm) and pA-Po(mm) and between pA-NPo(mm) and ANS-Me(mm) in occipitalized skulls are 0.575248 and 0.449058 respectively (Table 29). The probabilities are less than 0.05 for the pA-NPo(mm)/pA-Po(mm) relationship and somewhat greater than 0.05 for the pA-NPo(mm)/ANS-Me(mm) relationship. These observations indicate that point A becomes more anterior in reference to the NPo line, as the lower face increases vertically among occipitalized skulls.

Ricketts' mandibular plane angle does not correlate statistically with any of the cranial base parameters in either the occipitalized or the normal group of skulls. The closest relationship is between FH-GoGn and cranial breadth (CrB) in the normal skull population, possessing a correlation coefficient of 0.406737 (Table 28).

FH-GoGn correlates significantly with other facial parameters in both groups. Significant correlations between FH-GoGn and FH-NPo and between FH-GoGn and NDBa-PtGn (NBa-PtGn) have been discussed previously. FH-GoGn has a very strong correlation with NDBa-GoGn (Group A) and NBa-GoGn (Group B),

because these parameters evaluate the same anatomical entity, the mandibular plane, using different reference lines. The correlation coefficients between FH-GoGn and NDBa-GoGn (Group A) and between FH-GoGn and NBa-GoGn (Group B) are 0.919788 and 0.883477 respectively, with probabilities well below 0.001 (Table 29). The relationship of FH-GoGn with SNA shows a significant correlation in normal skulls only; this relationship in occipitalized skulls bears no correlation at all. The correlation coefficient between FH-GoGn and SNA among Group B skulls is -0.497561, possessing a probability of 0.05. This relationship indicates that the mandibular plane angle (Ricketts) becomes more obtuse when SNA becomes more acute, thus reinforcing previous observations that, in normal skulls, the relationships between maxilla and mandible tend to interrelate with one another, while in occipitalized skulls the mandibular relationships tend to function independently of the maxillary ones.

FH-GoGn tends to correlate with SNB in normal skulls, but to a lesser extent in occipitalized skulls; neither correlation is statistically significant (Table 29). The correlation coefficients between FH-GoGn and SNB are -0.369141 (Group A) and -0.487469 (Group B). These relationships, particularly in normal skulls, tend to suggest that as the mandible becomes more retrusive, there is a downward thrust of the mandible, which is manifested by an increased FH-GoGn angle.

There are three facial height parameters which correlate with FH-GoGn in the normal skull population, but not at all within the occipitalized group. These measurements are pA-Po(mm), ANS-Me(mm) and N-pA:pA-Po x 100. The correlation coefficients between FH-GoGn and pA-Po(mm), ANS-Me(mm) and N-pA:pA-Po x 100 among the normal skulls are 0.579619, 0.540693 and -0.501389 respectively (Table 29). The probabilities of these relationships are less than 0.05. These relationships indicate that the FH-GoGn angle increases, or becomes

steeper, as the lower facial height increases in the normal skull population. The negative value of the correlation coefficient involving  $N-pA:pA-Po \times 100$  reflects the impact that  $pA-Po(mm)$  has on this ratio, since  $pA-Po(mm)$  is the denominator of the ratio. The lack of similar correlations among occipitalized skulls indicates the randomness of the mandibular parameters within this population. The mid-facial height measurements,  $N-pA(mm)$  and  $N-ANS(mm)$ , show no correlation with  $FH-GoGn$  in either group. The relationship between  $FH-GoGn$  and  $N-ANS:ANS-Me \times 100$ , although statistically insignificant, shows an interesting relationship. The correlation coefficients for the two groups are diametrically opposite one another. The correlation coefficients between  $FH-GoGn$  and  $N-ANS:ANS-Me \times 100$  are 0.411377 for Group A and -0.435757 for Group B. For normal skulls, the relationship is the result of the impact on the ratio caused by the lower facial height. Among the occipitalized skulls, the impact of the lower facial height is negated and replaced by a tendency for the mid-facial height portion of the ratio to influence Ricketts' mandibular plane angle.

The mandibular plane angle  $NDBa-GoGn$  or  $NBa-GoGn$  shows no significant correlations with the cranial base parameters in either group, similar to the relationships of  $FH-GoGn$  with the cranial base (Table 28). There is one tendency toward correlation in each group, although the correlation coefficients are not statistically significant. Among normal skulls,  $NBa-GoGn$  tends to correlate with the cranial breadth ( $CrB$ ), bearing a coefficient of 0.437835. This relationship suggests that the angle  $NBa-GoGn$  increases, as the width of the cranium increases. Among occipitalized skulls,  $NDBa-GoGn$  tends to correlate inversely with the length of the anterior cranial floor ( $S-N(mm)$ ), bearing a correlation coefficient of -0.432238. This relationship

suggests that the angle NDBa-GoGn increases, as the length of the anterior cranial floor decreases.

The relationships of NDBa-GoGn or NBa-GoGn with the other facial parameters are quite similar to those involving FH-GoGn, noting that both these measurements geometrically describe the same entity, the mandibular plane, using different reference lines. The real difference between these two measurements is the degree of cranial deflection (NDBa-FH or NBa-FH). Since the correlation coefficients between NDBa-GoGn or NBa-GoGn and FH-GoGn indicate a very tight relationship, it is no wonder that the relationships involving NDBa-GoGn or NBa-GoGn are similar to those involving FH-GoGn. Relationships between NDBa-GoGn or NBa-GoGn and FH-NPo, NDBa-PtGn or NBa-PtGn, and FH-GoGn have been cited previously. NBa-GoGn correlates significantly with SNB in normal skulls, whereas the relationship between NDBa-GoGn and SNB in occipitalized skulls is close to being significant. The correlation coefficients between NDBa-GoGn and SNB (Group A) and between NBa-GoGn and SNB (Group B) are  $-0.486885$  and  $-0.639546$  respectively (Table 29). The probabilities are slightly greater than 0.05 for Group A and less than 0.01 for Group B. This relationship indicates that the mandibular plane angle becomes more obtuse, or steeper, as the mandible becomes more retrusive in both groups, with a much tighter correlation in the normal skull population.

Other relationships that show some elements of statistically significant correlations are those involving NBa-GoGn with facial height parameters in the normal skull population (Group B). These similar relationships in the occipitalized skull population (Group A) are absolutely insignificant. NBa-GoGn correlates significantly with the lower facial height parameters, pA-Po(mm) and ANS-Me(mm), with probabilities hovering around 0.01. The correlation coefficients between NBa-GoGn and pA-Po(mm) and between NBa-GoGn and

ANS-Me(mm) are 0.611428 and 0.630919 respectively in Group B (Table 29).

These relationships indicate that the mandibular plane angle, as defined by NBa-GoGn, becomes steeper, as the lower facial height increases among normal skulls. This observation is non-existent in the occipitalized skull population.

NBa-GoGn tends to correlate with the mid-facial height, defined by N-pA(mm), among normal skulls; however, this correlation is not statistically significant. An even less significant relationship exists between NBa-GoGn and N-ANS(mm) among normal skulls, and no correlation exists between NDBa-GoGn and the mid-facial height parameters among occipitalized skulls. The correlation coefficients between NBa-GoGn and N-pA(mm) and between NBa-GoGn and N-ANS(mm) in Group B skulls are 0.479724 and 0.356485 respectively (Table 29). These relationships tend to suggest that the NBa-GoGn angle increases, as the mid-facial height increases in the normal skull population.

NBa-GoGn also correlates significantly with one facial height ratio and tends to correlate with the other among normal skulls only. The correlation coefficients between NBa-GoGn and  $N-ANS:ANS-Me \times 100$  and between NBa-GoGn and  $N-pA:pA-Po \times 100$  in Group B are -0.505282 and -0.432593 respectively (Table 29). The probability of the former relationship is less than 0.05, and that of the latter is somewhat greater than 0.05. These relationships suggest that the NBa-GoGn angle increases, as these ratios become smaller, once again illustrating the impact of the lower facial height parameters (the denominator in these ratios) on these relationships. This data further support the premise that facial measurements tend to be dependent on one another in the normal skull population, but become quite variable and tend to be independent of each other within the occipitalized skull population.

TABLE 28. CORRELATION COEFFICIENTS - CRANIO-FACIAL ANALYSIS I

Dependent Variable	Independent Variable	Group A	Group B	
<u>Ricketts Measurements</u>				
3 FH-NPo	vs. 24 CrB	-0.162013	-0.111282	
	25 CrL	0.268956	<u>-0.560919</u>	
	12 DBa (Ba)-ML (mm)	-0.4524	<u>-0.562411</u>	
	22 DBa (Ba)-PNSOp (mm)	-0.35116	-0.408908	
	23 OC-DGL (mm)	3.03107E-02	<u>0.599545</u>	
	19 S-DBa (Ba) (mm)	0.401803	-0.373497	
	20 S-N (mm)	0.244615	-0.282995	
	21 S-DBa (Ba) : S-N x 100	0.226426	-6.68309E-02	
	1 N-S-DBa (Ba)	0.33055	0.315393	
	2 NDBa (Ba)-FH	0.357536	0.31556	
	10 SN-FH	0.360768	0.434272	
	4 NDBa (Ba)-PtGn	vs. 24 CrB	<u>-0.565132</u>	-0.330836
		25 CrL	0.072577	-0.11755
12 DBa (Ba)-ML (mm)		3.26976E-02	-3.08777E-02	
22 DBa (Ba)-PNSOp (mm)		0.110865	-0.363019	
23 OC-DGL (mm)		-0.261363	4.46352E-02	
19 S-DBa (Ba) (mm)		-8.71652E-02	-0.300837	
20 S-N (mm)		0.300102	-0.132167	
21 S-DBa (Ba) : S-N x 100		-0.273351	-0.145062	
1 N-S-DBa (Ba)		0.248625	0.453836	
2 NDBa (Ba)-FH		<u>-0.50801</u>	<u>-0.571885</u>	
10 SN-FH		-0.233404	-0.160855	

TABLE 28. CORRELATION COEFFICIENTS - CRANIO-FACIAL ANALYSIS I (Continued)

Dependent Variable	Independent Variable	Group A	Group B
6 pA-NPo (mm)	vs. 24 CrB	0.453648	-2.32308E-02
	25 CrL	-0.167733	0.244696
	12 DBa (Ba)-ML (mm)	0.292467	-0.156408
	22 DBa (Ba)-PNSOp (mm)	-2.53028E-02	0.366163
	23 OC-DGL (mm)	7.45188E-02	-8.50526E-02
	19 S-DBa (Ba) (mm)	-2.30522E-02	0.444392
	20 S-N (mm)	0.021811	0.153219
	21 S-DBa (Ba):S-N x 100	-4.85232E-02	0.253887
	1 N-S-DBa (Ba)	0.281824	1.06763E-03
	2 NDBa (Ba)-FH	-9.82051E-02	0.248767
	10 SN-FH	0.165407	0.266008
11 FH-GoGn	vs. 24 CrB	0.255635	0.406737
	25 CrL	-0.244968	0.141481
	12 DBa (Ba)-ML (mm)	0.216835	0.235243
	22 DBa (Ba)-PNSOp (mm)	0.139508	8.47565E-02
	23 OC-DGL (mm)	6.05158E-02	-0.366234
	19 S-DBa (Ba) (mm)	-0.341488	0.158037
	20 S-N (mm)	-0.356675	0.243671
	21 S-DBa (Ba):S-N x 100	-9.38718E-02	-9.88331E-02
	1 N-S-DBa (Ba)	-0.388446	8.69066E-02
	2 NDBa (Ba)-FH	-0.248002	-0.17644
	10 SN-FH	-0.341026	-4.08217E-02

TABLE 28. CORRELATION COEFFICIENTS - CRANIO-FACIAL ANALYSIS I (Continued)

Dependent Variable	Independent Variable	Group A	Group B
<u>Other Mandibular Plane Angle</u>			
5 NDBa(Ba)-GoGn	vs. 24 CrB	0.355696	0.437835
	25 CrL	-0.189592	8.29635E-02
	12 DBa(Ba)-ML(mm)	-4.08979E-02	-2.13166E-02
	22 DBa(Ba)-PNSOp(mm)	-7.25758E-02	0.158707
	23 OC-DGL(mm)	0.254999	-0.130803
	19 S-DBa(Ba)(mm)	-0.151939	0.160708
	20 S-N(mm)	-0.432238	0.208403
	21 S-DBa(Ba):S-N x 100	0.136506	-6.42377E-02
	1 N-S-DBa(Ba)	-0.398897	1.06763E-03
	2 NDBa(Ba)-FH	0.143827	0.248767
	10 SN-FH	-9.86674E-02	0.266008

The number preceding each variable indicates the position of that variable within the correlation coefficient matrix.

The underlined correlation coefficients are statistically significant to at least the 0.05 confidence level.

See Appendix for critical values of the correlation coefficients.

TABLE 29. CORRELATION COEFFICIENTS AMONG FACIAL PARAMETERS I

Dependent Variable	Independent Variable	Group A	Group B
<u>Ricketts Measurements</u>			
3 FH-NPo	vs. 4 NDBa(Ba)-PtGn	<u>0.571767</u>	<u>0.506411</u>
	5 NDBa(Ba)-GoGn	<u>-0.70363</u>	<u>-0.487931</u>
	11 FH-GoGn	<u>-0.839611</u>	<u>-0.62987</u>
	8 SNB	<u>0.50766</u>	<u>0.464312</u>
	13 N-pA(mm)	<u>-0.265527</u>	<u>-0.479621</u>
	16 N-ANS(mm)	<u>-0.269101</u>	<u>-0.462773</u>
4 NDBa(Ba)-PtGn	vs. 3 FH-NPo	<u>0.571767</u>	<u>0.506411</u>
	5 NDBa(Ba)-GoGn	<u>-0.789411</u>	<u>-0.723522</u>
	11 FH-GoGn	<u>-0.583863</u>	<u>-0.500789</u>
	7 SNA	<u>0.5863</u>	<u>0.181288</u>
	8 SNB	<u>0.704463</u>	<u>0.619213</u>
	13 N-pA(mm)	<u>-0.546883</u>	<u>-0.660154</u>
	16 N-ANS(mm)	<u>-0.529534</u>	<u>-0.524173</u>
	17 ANS-Me(mm)	<u>-0.338222</u>	<u>-0.478143</u>
6 pA-NPo(mm)	vs. 3 FH-NPo	<u>-0.46656</u>	<u>-0.040938</u>
	7 SNA	<u>3.58824E-02</u>	<u>0.654803</u>
	8 SNB	<u>-0.554413</u>	<u>1.84868E-02</u>
	9 ANB	<u>0.955204</u>	<u>0.963387</u>
	14 pA-Po(mm)	<u>0.575248</u>	<u>0.180436</u>
	17 ANS-Me(mm)	<u>0.449058</u>	<u>0.208708</u>

TABLE 29. CORRELATION COEFFICIENTS AMONG FACIAL PARAMETERS I (Continued)

Dependent Variable	Independent Variable	Group A	Group B
11 FH-GoGn	vs. 3 FH-NPo	<u>-0.839611</u>	<u>-0.62987</u>
	4 NDBa(Ba)-PtGn	<u>-0.583863</u>	<u>-0.500789</u>
	5 NDBa(Ba)-GoGn	<u>0.919788</u>	<u>0.883477</u>
	7 SNA	-0.169013	<u>-0.497561</u>
	8 SNB	-0.369141	-0.487469
	14 pA-Po(mm)	-3.62282E-02	<u>0.579619</u>
	17 ANS-Me(mm)	-0.111955	<u>0.540693</u>
	15 N-pA:pA-Po x 100	0.284095	<u>-0.501389</u>
	18 N-ANS:ANS-Me x 100	0.411377	-0.435757
<u>Other Mandibular Plane Angle</u>			
5 NDBa(Ba)-GoGn	vs. 3 FH-NPo	<u>-0.70363</u>	-0.487931
	4 NDBa(Ba)-PtGn	<u>-0.789411</u>	<u>-0.723522</u>
	11 FH-GoGn	<u>0.919788</u>	<u>0.883477</u>
	8 SNB	-0.486885	<u>-0.639546</u>
	13 N-pA(mm)	0.221724	0.479724
	16 N-ANS(mm)	0.229726	0.356485
	14 pA-Po(mm)	3.80512E-02	<u>0.611428</u>
	17 ANS-Me(mm)	-2.58361E-02	<u>0.630919</u>
	15 N-pA:pA-Po x 100	0.255587	-0.432593
18 N-ANS:ANS-Me x 100	0.319415	<u>-0.505282</u>	

TABLE 29. CORRELATION COEFFICIENTS AMONG FACIAL PARAMETERS I (Continued)

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The number preceding each variable indicates the position of that variable within the correlation coefficient matrix.

The underlined correlation coefficients are statistically significant to at least the 0.05 confidence level.

See Appendix for critical values of the correlation coefficients.

### Steiner Parameters

The correlations involving the Steiner measurements (SNA, SNB and ANB) are reported next. The relationships between SNA and the cranial base parameters are all statistically insignificant in the normal skull population. Among the occipitalized skulls, one statistically significant correlation exists. SNA significantly correlates with SN-FH in Group A, with a correlation coefficient of  $-0.638303$  (probability less than  $0.01$ ). The coefficient of the same relationship in Group B is  $-0.406583$ , which is statistically insignificant, although a slight tendency towards significance exists (Table 30). As the SN-FH angle increases, the SNA angle decreases. This relationship seems logical, since both parameters involve the orientation of line SN. If the SN line increases in its inclination (Sella moving inferiorly), then the angle subtended at Nasion (SNA) would become smaller, providing point A did not vary greatly in its orientation. The difference in the coefficients between the two groups can be explained by variations in the SN line. The orientation of the SN line varies to such a degree in the occipitalized population, that its impact overrides minor variations in the orientation of the NA line, thus producing a very significant correlation. Conversely, the SN line varies to a lesser degree in normal skulls, allowing the variations of the NA line to detract from the statistical significance between these two angular relationships.

SNA tends to correlate with NDBa-FH in the occipitalized group, although not of statistical significance, but the same relationship among normal skulls shows absolutely no correlation. The correlation coefficient involving SNA and NDBa-FH is  $-0.469985$ , suggesting that SNA varies inversely with the angle of the cranial deflection within Group A (Table 30). Taking into consideration that the correlation coefficients between SN-FH and

NDBa-FH or NBa-FH are 0.63289 (Group A) and 0.652869 (Group B) (probabilities less than 0.01) and that the NDBa or NBa line varies directly with the SN line, it is not surprising that the SNA angle tends to vary inversely with Huxley's line, by the mechanism noted in the previous paragraph. Since the NDBa or NBa and SN lines vary together and since these lines vary to a greater extent in the occipitalized skull population, their effects produce a greater impact on SNA in this population than among the normal skulls.

SNA shows a tendency to correlate with the length of the clivus (S-Ba(mm)) in the normal skull population, but not among occipitalized skulls. The correlation coefficient between SNA and S-Ba(mm) in Group B is 0.441381, while it is only 0.194544 for the similar relationship in Group A (Table 30). The SNA angle tends to increase as the length of the clivus increases, suggesting that the length of the clivus influences the orientation of the SN line, by affecting the position of Sella. This tentative relationship is not evident among occipitalized skulls. SNA also tends to correlate with the ratio S-Ba:S-N x 100 in normal skulls, exhibiting a correlation coefficient of 0.414113. This ratio tends to reinforce the influence that S-Ba(mm) has on the SNA angle, primarily the SN component.

SNA has some significant correlations with other facial measurements. The relationships between SNA and FH-GoGn and between SNA and NDBa-PtGn or NBa-PtGn have been discussed previously. SNA correlates very strongly with SNB in both skull populations. The correlation coefficients between SNA and SNB are 0.794967 for Group A and 0.746431 for Group B (Table 31). The probabilities of these coefficients are less than 0.001. Since both measurements use the same reference line, these relationships indicate that the mandible and maxilla move forward and backward in a coordinated pattern, or in concert with one another. Looking at this relationship from another perspective, it

may be that the correlation between SNA and SNB occurs purely because of variation in the orientation of the SN line, Sella specifically.

SNA also correlates significantly with ANB in normal skulls only, possessing a correlation coefficient of 0.68594, with a probability of less than 0.01 (Table 31). This relationship does not correlate at all within the occipitalized skull population. Among normal skulls, the angle ANB, which measures the relationship between the maxilla and mandible in an anterior-posterior direction, is a dependent function of the anterior-posterior variation of the maxilla; as the SNA angle increases, so does the ANB angle. This dependency does not exist among occipitalized skulls. These relationships are born out again, when the correlation between SNA and pA-NPo(mm) is evaluated in both groups. The correlation coefficient between SNA and pA-NPo(mm) is 0.654803 in Group B, with a probability of less than 0.01, but the coefficient in Group A is totally insignificant. This observation indicates that point A moves further anterior in relation to the NPo line, as the SNA angle increases in normal skulls. This relationship does not occur in occipitalized skulls, probably because of greater variation of the NPo line, Pogonion in particular, in this skull population.

One tendency toward correlation involving SNA occurs in the occipitalized population, but is absolutely insignificant among normal skulls. That relationship is between SNA and  $N-pA:pA-Po \times 100$ , with a correlation coefficient of -0.472424, with a probability slightly greater than 0.05 (Table 31). This tendency toward correlation indicates that the SNA angle becomes larger, as the mid-facial height becomes smaller in relation to the lower facial height in Group A skulls. However, this observation is negated by the fact that SNA does not correlate with the other ratio of facial heights ( $N-ANS:ANS-Me \times 100$ ) in either group.

The relationships between SNB and the cranial base parameters show one significant correlation within both groups and one tendency toward correlation in both groups (Table 30). SNB correlates significantly with SN-FH, bearing correlation coefficients of  $-0.610705$  (Group A) and  $-0.564586$  (Group B). The probabilities of these correlations are less than 0.05. As SN-FH increases, SNB decreases. This relationship is a function of the orientation of the Sella-Nasion line, Sella particularly, which was discussed concerning the correlation between SNA and SN-FH. The tentative correlation involves SNB and the breadth of the cranium (CrB), possessing correlation coefficients of  $-0.47112$  (Group A) and  $-0.45113$  (Group B). The probabilities are greater than 0.05 for both groups. This tendency suggests that the SNB angle becomes smaller, as the cranial width increases. It can be postulated that this effect is the result of the downward migration of Sella, instead of the posterior positioning of point B. This interpretation can be inferred by comparing the correlations between SN-FH and the cranial breadth, possessing correlation coefficients of  $0.382922$  for Group A and  $0.312728$  for Group B (Table 27), and between FH-NPo and the cranial breadth, demonstrating correlation coefficients of  $-0.162013$  for Group A and  $-0.111282$  for Group B (Table 28).

There are several statistically significant correlations between SNB and other facial measurements. The relationships between SNB and FH-NPo, NDBa-PtGn (NBa-PtGn), pA-NPo(mm), NDBa-GoGn (NBa-GoGn), and SNA have been discussed in previous paragraphs. SNB tends to correlate with ANB in occipitalized skulls only; absolutely no correlation exists in normal skulls. The correlation coefficient in Group A between SNB and ANB is  $-0.478497$ , having a probability slightly greater than 0.05 (Table 31). This observation suggests that ANB (the relationship between the maxilla and mandible in the anterior-posterior direction) tends to correlate inversely with SNB (the

orientation of the mandible to the cranial base) among occipitalized skulls, but not in the normal group. If the relationship between SNB and pA-NPo(mm) is taken into consideration, where the correlation is significant at less than the 0.05 confidence level in Group A only, then it appears that the angle ANB is an inverse function of the anterior-posterior position of the mandible in occipitalized skulls. On the other hand, ANB is dependent upon the anterior-posterior position of the maxilla (SNA) in the normal skull population.

SNB also correlates significantly with the mid-facial height by both measurements among normal skulls, and marginal tendencies exist among the occipitalized skulls. There are no significant correlations or tendencies between SNB and the lower facial height parameters in either population. The correlation coefficients between SNB and N-pA(mm) and between SNB and N-ANS(mm) are -0.596691 and -0.527279 in Group B (normal skulls) and -0.471816 and -0.385113 in Group A (occipitalized skulls) respectively (Table 31). The probabilities of the coefficients in Group B are less than 0.05; that of SNB and N-pA(mm) in Group A is slightly greater than 0.05; and that of SNB and N-ANS(mm) in Group A is insignificant. These relationships indicate that the SNB angle decreases, or the mandible becomes oriented more posteriorly, as the midface increases in vertical length for the normal skull population. Similar relationships tend to exist in the occipitalized population, but they are not statistically significant.

The relationships between ANB and the cranial base parameters indicate one statistically significant correlation and one tendency toward correlation among the normal skull population, but no correlations among the occipitalized skulls. The correlation coefficients between ANB and Ba-PNSOp(mm) or DBa-PNSOp(mm) are 0.509547 and -0.054695 for Groups B and A respectively (Table 30). The probabilities are slightly less than 0.05 for Group B and

completely insignificant for Group A. Since the relationships between ANB and the other basilar impression-related measurements are completely insignificant, there is some doubt about the validity of this correlation between ANB and Ba-PNSOp(mm). It appears that this correlation does not involve the movement of the point Ba, but relates to variations in the PNS-Op line, particularly the orientation of point PNS and the entire bony palate. The statistically significant correlation between Ba-PNSOp(mm) and the mid-facial height measurements in the normal skull population must be considered, which apparently affects the downward orientation of the palate as related to Basion. Consequently, the relationship between Ba-PNSOp(mm) and ANB indicates that the ANB angle increases, as the PNS-Op line becomes more caudad in relation to Basion, reflecting the more caudad position of the palate. This correlation is negated in occipitalized skulls by the great variation in the position of Derived Basion (DBa).

ANB also tends to correlate with the length of the clivus (S-Ba(mm)) in the normal skull group, bearing a correlation coefficient of 0.480574, with a probability slightly greater than 0.05 (Table 30). This relationship is totally insignificant within the occipitalized group. As the length of the clivus increases in normal skulls, so does the ANB angle, reflecting the general size coordination of the cranial base-mid-face complex in both inferior-superior and anterior-posterior directions. Again, because of the great variability in the region of the foramen magnum in occipitalized skulls, this relationship is negated.

ANB correlates significantly with several other facial measurements. Relationships between ANB and pA-NPo(mm), SNA, and SNB have been discussed previously. ANB tends to correlate with FH-NPo in the occipitalized skull population, but not at all among normal skulls. The correlation coefficient

between ANB and FH-NPo in Group A is  $-0.453621$ , with a probability somewhat greater than 0.05 (Table 31). This relationship suggests that the ANB angle becomes larger, as the FH-NPo angle decreases, or as the point Pogonion moves posteriorly. As with the discussion relating SNB and ANB, ANB is more dependent on the mandibular anterior-posterior positioning in occipitalized skulls than on the anterior-posterior orientation of the maxilla.

There is another tendency toward correlation between ANB and the lower facial height measurement pA-Po(mm) in occipitalized skulls. The correlation coefficient between ANB and pA-Po(mm) in Group A is  $0.483051$ , indicating a probability slightly greater than 0.05 (Table 31). This correlation in Group B is quite insignificant, possessing a correlation coefficient of  $0.181425$ . The relationships involving ANB and the other lower facial height measurement ANS-Me(mm) is insignificant in both groups. Because of a lack in consistency of this data, the validity of the tentative correlation between ANB and pA-Po(mm) in occipitalized skulls is questioned.

TABLE 30. CORRELATION COEFFICIENTS - CRANIO-FACIAL ANALYSIS II

Dependent Variable	Independent Variable	Group A	Group B	
<u>Steiner Measurements</u>				
7 SNA	vs. 24 CrB	-0.299366	-0.334179	
	25 CrL	-0.211587	0.18313	
	12 DBa (Ba)-ML (mm)	-5.64019E-02	-0.205891	
	22 DBa (Ba)-PNSOp (mm)	-0.178992	0.120303	
	23 OC-DGL (mm)	-8.26142E-02	6.32901E-02	
	19 S-DBa (Ba) (mm)	0.194544	0.441381	
	20 S-N (mm)	8.05087E-02	0.18908	
	21 S-DBa (Ba) : S-N x 100	0.150866	0.414113	
	1 N-S-DBa (Ba)	-0.173705	-0.294008	
	2 NDBa (Ba)-FH	-0.469985	-4.82678E-02	
	10 SN-FH	<u>-0.638303</u>	-0.406583	
	8 SNB	vs. 24 CrB	-0.47112	-0.451133
		25 CrL	-7.75528E-02	-2.81504E-02
		12 DBa (Ba)-ML (mm)	-0.194038	-0.205111
22 DBa (Ba)-PNSOp (mm)		-0.125456	-0.300724	
23 OC-DGL (mm)		-0.162634	0.120064	
19 S-DBa (Ba) (mm)		0.190606	0.166844	
20 S-N (mm)		3.30119E-02	-0.13316	
21 S-DBa (Ba) : S-N x 100		0.182759	0.323909	
1 N-S-DBa (Ba)		-0.295038	-0.116245	
2 NDBa (Ba)-FH		-0.31166	-0.375737	
10 SN-FH		<u>-0.610705</u>	<u>-0.564586</u>	

TABLE 30. CORRELATION COEFFICIENTS - CRANIO-FACIAL ANALYSIS II (Continued)

Dependent Variable	Independent Variable	Group A	Group B
9 ANB	vs. 24 CrB	0.334288	-8.54228E-03
	25 CrL	-0.179916	0.305909
	12 DBa(Ba)-ML(mm)	0.234494	-8.49921E-02
	22 DBa(Ba)-PNSOp(mm)	-0.054685	<u>0.509547</u>
	23 OC-DGL(mm)	0.145388	-3.62172E-02
	19 S-DBa(Ba)(mm)	-2.89488E-02	0.480574
	20 S-N(mm)	0.062748	0.17401
	21 S-DBa(Ba):S-N x 100	-7.94067E-02	0.268109
	1 N-S-DBa(Ba)	0.229257	-0.314528
	2 NDBa(Ba)-FH	-0.172511	0.338356
	10 SN-FH	0.07107	6.62052E-03

The number preceding each variable indicates the position of that variable within the correlation coefficient matrix.

The underlined correlation coefficients are statistically significant to at least the 0.05 confidence level.

See Appendix for critical values of the correlation coefficients.

TABLE 31. CORRELATION COEFFICIENTS AMONG FACIAL PARAMETERS II

Dependent Variable	Independent Variable	Group A	Group B
<u>Steiner Measurements</u>			
7 SNA	vs. 4 NDBa(Ba)-PtGn	<u>0.5863</u>	0.181288
	6 pA-NPo(mm)	3.58824E-02	<u>0.654803</u>
	11 FH-GoGn	-0.169013	<u>-0.497561</u>
	8 SNB	<u>0.794967</u>	<u>0.746431</u>
	9 ANB	0.15228	<u>0.68594</u>
	15 N-pA:pA-Po x 100	-0.472424	-6.46573E-02
8 SNB	vs. 3 FH-NPo	<u>0.507661</u>	0.464312
	4 NDBa(Ba)-PtGn	<u>0.704463</u>	<u>0.619213</u>
	5 NDBa(Ba)-GoGn	-0.486885	<u>-0.639546</u>
	6 pA-NPo(mm)	<u>-0.554413</u>	1.84868E-02
	7 SNA	<u>0.794967</u>	<u>0.746431</u>
	9 ANB	-0.478497	2.77772E-02
	13 N-pA(mm)	-0.471816	<u>-0.596691</u>
	16 N-ANS(mm)	-0.385113	<u>-0.527279</u>
9 ANB	vs. 3 FH-NPo	-0.453621	-4.35807E-02
	6 pA-NPo(mm)	<u>0.955204</u>	<u>0.963387</u>
	7 SNA	0.15228	<u>0.68594</u>
	8 SNB	-0.478497	2.77772E-02
	14 pA-Po(mm)	0.483051	0.181425

TABLE 31. CORRELATION COEFFICIENTS AMONG FACIAL PARAMETERS II (Continued)

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The number preceding each variable indicates the position of that variable within the correlation coefficient matrix.

The underlined correlation coefficients are statistically significant to at least the 0.05 confidence level.

See Appendix for critical values of the correlation coefficients.

### Facial Height Parameters

The facial height measurements correlate significantly with several cranial base parameters, particularly within the normal skull population. Since the two methods of determining mid-facial height, lower facial height, and their two ratios are quite similar, these paired relationships are discussed somewhat together. Mid-facial height measurement N-pA(mm) correlates significantly with the cranial breadth (CrB) in both groups and with the cranial length (CrL), Ba-PNSOp(mm), S-Ba(mm) and S-N(mm) in the normal skull population only (Table 32). The correlation coefficients between N-pA(mm) and CrB are 0.65048 (Group A) and 0.565058 (Group B). The probability for Group A is less than 0.01 and for Group B, less than 0.05. This relationship indicates that the mid-facial height (N-pA(mm)) varies directly with the cranial breadth in both populations. The correlation coefficients between N-pA(mm) and the cranial length (CrL) are 0.527873 (Group B) and 0.170279 (Group A). The probability for Group B is less than 0.05 and is insignificant regarding Group A. Mid-facial height, then, is a function of the cranial length in normal skulls, but not among the occipitalized skull population.

The same relationships are true when correlating the mid-facial height N-pA(mm) with the length of the clivus (S-Ba(mm) or S-DBa(mm)) and with the length of the anterior cranial floor (S-N(mm)). The correlation coefficients of N-pA(mm) with S-Ba(mm) and with S-N(mm) in the normal skull population are 0.550395 and 0.630104 respectively (Table 32). The probability for the former is less than 0.05, and that of the latter is less than 0.01. The corresponding correlation coefficients in the occipitalized skull population are 0.191819 between N-pA(mm) and S-DBa(mm) and 0.309713 between N-pA(mm) and S-N(mm). Neither relationship is statistically significant.

The correlation between N-pA(mm) and Ba-PNSOp(mm) is statistically significant among normal skulls, with a coefficient of 0.653316, possessing a probability of less than 0.01 (Table 32). The similar relationship in occipitalized skulls is totally insignificant. No other correlations between N-pA(mm) and a basilar impression-related measurement are significant in either group. This significant correlation in Group B then depends on the downward growth of the palate, reflected in the orientation of the PNS-Op line, instead of the upward migration or invagination of Basion. In essence, the relationship between N-pA(mm) and Ba-PNSOp(mm) indicates that as the mid-facial height increases, the orientation of the palate moves downward as related to Basion in the normal skull population.

The relationships involving N-ANS(mm), the alternate method of measuring the mid-facial height, and the cranial base parameters are similar to those mentioned above. N-ANS(mm) correlates significantly in both groups with the cranial breadth (CrB), bearing correlation coefficients of 0.647972 for Group A and 0.601389 for Group B (Table 33). The probabilities are less than 0.01 for Group A and slightly greater than 0.01 for Group B. Among the normal skulls, N-ANS(mm) tends to correlate with the cranial length (CrL), having a correlation coefficient of 0.484616; the probability is slightly greater than 0.05. This same relationship among occipitalized skulls is statistically insignificant. Relationships between N-ANS(mm) and S-Ba(mm) or S-DBa(mm), S-N(mm), and Ba-PNSOp(mm) or DBa-PNSOp(mm) have similar results as N-pA(mm) has with these basal measurements. The correlation coefficients are 0.574545, 0.644569 and 0.527433 respectively in the normal skull population. The probabilities are less than 0.05 for N-ANS(mm) relationships involving S-Ba(mm) and Ba-PNSOp(mm) and less than 0.01 for the relationship between

N-ANS(mm) and S-N(mm). The statistical correlations for these three relationships among occipitalized skulls are insignificant.

There is one cranial base parameter that has a statistically significant correlation with N-ANS(mm), but only a marginal tendency with N-pA(mm) among normal skulls. That relationship is between N-ANS(mm) and Ba-ML(mm). The correlation coefficients between N-ANS(mm) and Ba-ML(mm) and between N-pA(mm) and Ba-ML(mm) are 0.514244 and 0.422522 respectively (Tables 32 and 33). The probabilities are less than 0.05 for the former and considerably greater than 0.05 for the latter. These relationships are insignificant in the occipitalized skull population. This data can be interpreted as a function of the Mastoid Line, or the downward growth or projection of the mastoid processes, instead of a function of the upward projection of Basion. This observation tends to indicate that the mid-facial height and the degree of downward growth of the mastoid processes coincide with one another.

It should be noted that these relationships cited between the mid-facial height and cranial base parameters are all linear measurements. These relationships are all a matter of size. If the entire skull increases in size, so will its parts increase in a proportional manner. This is what occurs in the normal skull population. As the skull becomes larger, the cranial length, the cranial breadth, the length of the clivus, the length of the anterior cranial floor, the mid-facial height, the posterior mid-facial height (as measured by the orientation of the Posterior Nasal Spine) and the mastoid processes all increase in relative proportions. The alterations and increased variability at the base of the skull in the occipitalized skull population negate most of these relationships. The only relationship between the mid-facial height and a cranial base parameter, which retains a

significant correlation in occipitalized skulls, is that between the mid-facial height measurements and the cranial breadth.

The mid-facial height measurements significantly correlate with other facial parameters. Relationships between N-pA(mm) and FH-NPo, NBa-PtGn or NDBa-PtGn, NBa-GoGn or NDBa-GoGn, and SNB and between N-ANS(mm) and FH-NPo, NBa-PtGn or NDBa-PtGn, and SNB have been discussed previously. Of course, N-pA(mm) has an extremely strong correlation with N-ANS(mm) in both populations, since both measurements examine essentially the same function. The correlation coefficients between these two mid-facial measurements are 0.951282 and 0.956009 for Groups A and B respectively (Table 34). The probabilities are exceedingly less than 0.001. The mid-facial height parameters also strongly correlate with the lower facial height measurements in both groups. The correlation coefficients between N-pA(mm) and pA-Po(mm) are 0.690603 and 0.693827 in Groups A and B respectively, establishing probabilities of less than 0.01. The correlation coefficients between N-pA(mm) and ANS-Me(mm) are 0.794645 for Group A and 0.708293 for Group B. The probabilities are less than 0.001 for occipitalized skulls and less than 0.01 for normal skulls. Similar relationships exist between N-ANS(mm) and the lower facial height measurements. The correlation coefficients between N-ANS(mm) and pA-Po(mm) are 0.661283 and 0.639291 for Groups A and B respectively, possessing probabilities of less than 0.01 in both groups. The correlation coefficients between N-ANS(mm) and ANS-Me(mm) for Groups A and B respectively are 0.743136 and 0.614612. The probability of the former is slightly less than 0.001, and that of the latter is slightly greater than 0.01. Since all four parameters are linear measurements, these relationships indicate that the mid-facial height and the lower facial height grow proportionally with one another in both groups. It is interesting to note that the mid-facial height

does not correlate significantly with the ratios of facial heights ( $N-pA:pA-Po \times 100$  and  $N-ANS:ANS-Me \times 100$ ) in either the normal or occipitalized population.

The lower facial height measurements correlate with the cranial base parameters in a similar fashion to the relationships involving the mid-facial height measurements, with one exception in each group. The relationships correlating  $pA-Po(mm)$  and  $ANS-Me(mm)$  with the cranial breadth ( $CrB$ ) are statistically significant within the occipitalized skull population, but insignificant in the normal skull group, although some tendencies do exist. The correlation coefficients between  $pA-Po(mm)$  and  $CrB$  and between  $ANS-Me(mm)$  and  $CrB$  are 0.521234 and 0.560009 respectively in Group A, with probabilities of less than 0.05 for both relationships (Tables 32 and 33). The correlation coefficients between the same parameters in Group B are 0.405025 and 0.485261 respectively; the probability of the correlation coefficient between  $ANS-Me(mm)$  and  $CrB$  is slightly greater than 0.05. In contrast, these lower facial height measurements correlate significantly with the cranial length among normal skulls, but are insignificant among occipitalized skulls. The correlation coefficients between  $pA-Po(mm)$  and  $CrL$  and between  $ANS-Me(mm)$  and  $CrL$  are 0.596598 and 0.563707 respectively in Group B, while they are 0.372779 and 0.380066 in Group A. The probabilities of the Group B relationships are less than 0.05.

Similarly, the lower facial height measurements correlated significantly with the  $Ba-PNSOp(mm)$  and  $S-N(mm)$  parameters in the normal skull population, but not in the occipitalized skull population. The correlation coefficients between  $pA-Po(mm)$  and  $Ba-PNSOp(mm)$  and between  $ANS-Me(mm)$  and  $Ba-PNSOp(mm)$  in Group B are 0.50822 and 0.539632 respectively, while the coefficients dealing with the same relationships in Group A are -0.275086 and

-0.248839 respectively (Tables 32 and 33). The probabilities for the Group B correlations are less than 0.05. The correlation coefficients between pA-Po(mm) and S-N(mm), the length of the anterior cranial floor and between ANS-Me(mm) and S-N(mm) are 0.805697 and 0.767707 respectively among normal Group B skulls, while the coefficients involving the same relationships within the occipitalized Group A population are 0.37756 and 0.396129 respectively. The probabilities of the Group B correlations are less than 0.001.

It is somewhat surprising that the lower facial height measurements correlate significantly with the length of the clivus in the occipitalized skull population as well as in the normal skull population. It is noted that the length of the skull, length of the anterior cranial floor, and the relationship between Derived Basion and Chamberlain's line do not correlate significantly with the lower facial height parameters among occipitalized skulls. The correlation coefficients between pA-Po(mm) and S-Ba(mm) and between ANS-Me(mm) and S-Ba(mm) are 0.614709 and 0.581741 respectively among normal skulls, while the coefficients of the corresponding relationships in the occipitalized skull population are 0.509294 and 0.563318 respectively (Tables 32 and 33). The probabilities of all four coefficients are less than 0.05. It is also interesting to note that the lower as well as the mid-facial heights do not correlate with the angular relationships of the cranial base, S-N-Ba or S-N-DBa, NBa-FH or NDBa-FH, and SN-FH, in either group.

To summarize, the lower facial height correlates with the cranial length, length of the anterior cranial floor, length of the clivus, and the posterior mid-facial height, as measured by Ba-PNSOp(mm), in the normal skull population. On the other hand, the lower facial height correlates only with the cranial breadth and the length of the clivus within the occipitalized skull population. It would be expected that these relationships would vary

proportionally, according to the size of the skull. This correlation is primarily the case within the normal skull population. The fact that they do not correlate in the occipitalized skull population as well tends to indicate that these relationships (cranial length, anterior cranial floor length, and posterior mid-facial height) do not impact directly on the lower facial height. However, the relationship involving the posterior mid-facial height (DBa-PNSOp(mm)) within the occipitalized skull population may be erroneously insignificant due to the greater variation of Derived Basion within that group. Since the lower facial height measurements do not correlate significantly in either group with the cranial breadth, then the cranial breadth does not significantly impact on the lower facial height development. The observation that the length of the clivus significantly correlates with the lower facial height in both groups indicates that the lower facial height is directly influenced by or dependent upon the length of the clivus, particularly when it is noted that the angular measurements of the cranial base are not correlated with the lower facial height.

The lower facial height measurements correlate or tend to correlate with other facial analysis parameters. The relationships of the lower facial height measurements, pA-Po(mm) and ANS-Me(mm), with NDBa-PtGn or NBa-PtGn, pA-NPo(mm), FH-GoGn, NDBa-GoGn or NBa-GoGn, ANB and the mid-facial height parameters, N-pA(mm) and N-ANS(mm), have been discussed in previous sections. Of course, one lower facial height measurement strongly correlates with the other in both groups. The correlation coefficients between pA-Po(mm) and ANS-Me(mm) are 0.96698 and 0.969362 in Groups A and B respectively (Table 34). The probabilities are exceedingly less than 0.001.

The lower facial height measurements correlate significantly with the ratios comparing mid-facial heights with lower facial heights among normal

skulls. The correlation coefficients of pA-Po(mm) with N-pA:pA-Po x 100 and with N-ANS:ANS-Me x 100 in Group B are -0.740398 and -0.660804 respectively, whereas the coefficients between ANS-Me(mm) and N-pA:pA-Po x 100 and between N-ANS:ANS-Me x 100 are -0.686172 and -0.722251 respectively among normal skulls (Table 34). In the occipitalized skull population, pA-Po(mm) and ANS-Me(mm) correlate statistically with the ratio N-ANS:ANS-Me x 100, but not with the ratio N-pA:pA-Po x 100. The correlation coefficients relating pA-Po(mm) and ANS-Me(mm) with N-ANS:ANS-Me x 100 in Group A skulls are -0.736495 and -0.713459 respectively, while the coefficients relating pA-Po(mm) and ANS-Me(mm) with N-pA:pA-Po x 100 are -0.366837 and -0.194396 respectively in Group A. The probabilities for the first six correlation coefficients are less than 0.01, some closely approaching 0.001; the probabilities of the latter two coefficients are insignificant. Since the lower facial height measurements are the denominator of these mathematical relationships, the numerical values of the ratios decrease as the lower facial heights increase, providing the mid-facial height remains static. These relationships indicate that these facial height ratios are more dependent upon the lower facial height than the mid-facial height among normal skulls. This dependency also holds true in the occipitalized skull population regarding the ratio N-ANS:ANS-Me x 100. Concerning the relationships involving the ratio N-pA:pA-Po x 100 among occipitalized skulls, it appears that the mid-facial height has a greater influence in calculating this ratio, although not statistically significant, thus negating some of the influence of the lower facial height.

The facial height ratios are probably more important in detecting facial abnormalities of facial growth than pure linear measurements, since they measure proportional relationships and discount variation in the total

size of the face and skull. The correlations between the facial height ratios and the cranial base parameters are insignificant among normal skulls, although there is a tendency toward correlation between  $N-pA:pA-Po \times 100$  and the length of the anterior cranial floor, exhibiting a correlation coefficient of  $-0.49492$  (Table 32). The similar relationship involving the ratio  $N-ANS:ANS-Me \times 100$  and  $S-N(mm)$  is statistically insignificant (Table 33). Both relationships are insignificant in the occipitalized population. There is one relationship that is statistically significant among occipitalized skulls.  $N-ANS:ANS-Me \times 100$  correlates significantly with the length of the clivus ( $S-DBa(mm)$ ), bearing a correlation coefficient of  $-0.631215$  (probability of less than 0.01). This relationship does not correlate significantly regarding the other facial height ratio,  $N-pA:pA-Po \times 100$ , among occipitalized skulls, and neither facial height ratio correlates with the length of the clivus among normal skulls. The correlations between  $N-pA:pA-Po \times 100$  and  $S-N(mm)$  in Group B and between  $N-ANS:ANS-Me \times 100$  and  $S-DBa(mm)$  in Group A reflect the strong statistical impact that  $S-N(mm)$  has on the lower facial height  $pA-Po(mm)$  and the length of the clivus has on the lower facial height  $ANS-Me(mm)$  in their respective groups. The meaningful relationships comparing the ratio within the base of the skull ( $S-DBa:S-N \times 100$  or  $S-Ba:S-N \times 100$ ) with the facial height ratios indicate no statistically significant correlations in either group.

The significant or tentatively significant relationships of the facial height ratios and the facial analysis parameters have been discussed previously. Those relationships cited elsewhere in this section involve the mandibular plane angles  $FH-GoGn$  and  $NDBa-GoGn$  or  $NBa-GoGn$ ,  $SNA$ , and the lower facial height parameters  $pA-Po(mm)$  and  $ANS-Me(mm)$ . The relationship remaining is the correlation between one facial height ratio with the other (Table 34).

$N-pA:pA-Po \times 100$  correlates significantly with  $N-ANS:ANS-Me \times 100$  in both groups, with correlation coefficients of 0.673699 (Group A) and 0.866191 (Group B). The probabilities are less than 0.01 for Group A and less than 0.001 for Group B. The difference in the coefficients and their probabilities is probably due to slightly greater variation in the distances  $ANS-pA$  and  $Po-Me$  in Group A; these distances are the differences between the two facial height measurement schemes.

TABLE 32. CORRELATION COEFFICIENTS - CRANIO-FACIAL HEIGHT ANALYSIS I

Dependent Variable	Independent Variable	Group A	Group B	
13 N-pA(mm)	vs. 24 CrB	<u>0.65048</u>	<u>0.565058</u>	
	25 CrL	0.170279	<u>0.527873</u>	
	12 DBa(Ba)-ML(mm)	0.291029	0.422522	
	22 DBa(Ba)-PNSOp(mm)	6.36449E-02	<u>0.653316</u>	
	23 OC-DGL(mm)	-8.38773E-02	-0.209629	
	19 S-DBa(Ba)(mm)	0.191819	<u>0.550395</u>	
	20 S-N(mm)	0.309713	<u>0.630104</u>	
	21 S-DBa(Ba):S-N x 100	-0.060731	-0.12148	
	1 N-S-DBa(Ba)	6.25436E-02	-0.167633	
	2 NDBa(Ba)-FH	0.218757	0.229954	
	10 SN-FH	0.266173	0.151531	
	14 pA-Po(mm)	vs. 24 CrB	<u>0.521234</u>	0.405025
		25 CrL	0.372779	<u>0.596598</u>
12 DBa(Ba)-ML(mm)		-3.03192E-02	0.402579	
22 DBa(Ba)-PNSOp(mm)		-0.275086	<u>0.50822</u>	
23 OC-DGL(mm)		-0.183024	-0.277956	
19 S-DBa(Ba)(mm)		<u>0.509294</u>	<u>0.614709</u>	
20 S-N(mm)		0.37756	<u>0.805697</u>	
21 S-DBa(Ba):S-N x 100		0.17946	-0.214251	
1 N-S-DBa(Ba)		0.228503	-0.120642	
2 NDBa(Ba)-FH		0.313714	0.013093	
10 SN-FH		0.377551	-4.98142E-03	

TABLE 32. CORRELATION COEFFICIENTS - CRANIO-FACIAL HEIGHT ANALYSIS I

(Continued)

Dependent Variable	Independent Variable	Group A	Group B
15 N-pA:pA-Po x 100	vs. 24 CrB	0.197157	-3.52406E-02
	25 CrL	-0.30227	-0.295744
	12 DBa(Ba)-ML(mm)	0.381661	-0.134457
	22 DBa(Ba)-PNSOp(mm)	0.378265	-0.101012
	23 OC-DGL(mm)	-0.303191	0.171017
	19 S-DBa(Ba)(mm)	-0.364285	-0.329111
	20 S-N(mm)	-0.106721	-0.49492
	21 S-DBa(Ba):S-N x 100	-0.253492	0.16057
	1 N-S-DBa(Ba)	-0.203762	-1.39594E-02
	2 NDBa(Ba)-FH	-8.50897E-02	0.161397
	10 SN-FH	-0.128732	0.10869

The number preceding each variable indicates the position of that variable within the correlation coefficient matrix.

The underlined correlation coefficients are statistically significant to at least the 0.05 confidence level.

See Appendix for critical values of the correlation coefficients.

TABLE 33. CORRELATION COEFFICIENTS - CRANIO-FACIAL HEIGHT ANALYSIS II

Dependent Variable	Independent Variable	Group A	Group B	
16 N-ANS (mm)	vs. 24 CrB	<u>0.647972</u>	<u>0.601389</u>	
	25 CrL	0.196605	0.484616	
	12 DBa (Ba)-ML (mm)	0.23091	<u>0.514244</u>	
	22 DBa (Ba)-PNSOp (mm)	9.71459E-02	<u>0.527433</u>	
	23 OC-DGL (mm)	-5.87174E-02	-0.265119	
	19 S-DBa (Ba) (mm)	0.17111	<u>0.574545</u>	
	20 S-N (mm)	0.334908	<u>0.644569</u>	
	21 S-DBa (Ba):S-N x 100	-8.50418E-02	-0.105845	
	1 N-S-DBa (Ba)	-5.37904E-02	-0.06716	
	2 NDBa (Ba)-FH	0.182149	0.105724	
	10 SN-FH	0.15093	8.99206E-02	
	17 ANS-Me (mm)	vs. 24 CrB	<u>0.560009</u>	0.485261
		25 CrL	0.380066	<u>0.563707</u>
12 DEa (Ba)-ML (mm)		-3.59811E-02	0.321139	
22 DBa (Ba)-PNSOp (mm)		-0.248839	<u>0.539632</u>	
23 OC-DGL (mm)		0.153256	-0.179828	
19 S-DBa (Ba) (mm)		<u>0.563318</u>	<u>0.581741</u>	
20 S-N (mm)		0.396129	<u>0.767707</u>	
21 S-DBa (Ba):S-N x 100		0.214516	-0.209507	
1 N-S-DPa (Ba)		0.233314	-0.145238	
2 NDBa (Ba)-FH		0.352853	9.87973E-02	
10 SN-FH		0.390449	5.17024E-02	

TABLE 33. CORRELATION COEFFICIENTS - CRANIO-FACIAL HEIGHT ANALYSIS II  
(Continued)

Dependent Variable	Independent Variable	Group A	Group B
18 N-ANS:ANS-Me x 100 vs.	24 CrB	-0.123174	-8.38731E-02
	25 CrL	-0.392523	-0.2552
	12 DBa (Ba)-ML (mm)	0.202843	5.96456E-02
	22 DBa (Ba)-PNSOp (mm)	0.406868	-0.246454
	23 OC-DGL (mm)	-0.234626	-0.015747
	19 S-DBa (Ba) (mm)	<u>-0.631215</u>	-0.223743
	20 S-N (mm)	-0.242633	-0.373744
	21 S-DBa (Ba):S-N x 100	-0.379982	0.151672
	1 N-S-DBa (Ba)	-0.411311	0.109331
	2 NDBa (Ba)-FH	-0.328348	-6.24664E-02
	10 SN-FH	-0.433433	-1.56807E-02

The number preceding each variable indicates the position of that variable within the correlation coefficient matrix.

The underlined correlation coefficients are statistically significant to at least the 0.05 confidence level.

See Appendix for critical values of the correlation coefficients.

TABLE 34. CORRELATION COEFFICIENTS AMONG FACIAL PARAMETERS III

Dependent Variable	Independent Variable	Group A	Group B
<u>Facial Height Measurements</u>			
13 N-pA(mm)	vs. 3 FH-NPo	-0.265527	-0.479621
	4 NDBa(Ba)-PtGn	<u>-0.546883</u>	<u>-0.660154</u>
	5 NDBa(Ba)-GoGn	0.221724	0.479724
	8 SNB	-0.471816	<u>-0.596691</u>
	16 N-ANS(mm)	<u>0.951282</u>	<u>0.956009</u>
	14 pA-Po(mm)	<u>0.690603</u>	<u>0.693827</u>
	17 ANS-Me(mm)	<u>0.794645</u>	<u>0.708293</u>
14 pA-Po(mm)	vs. 4 NDBa(Ba)-PtGn	-0.328524	-0.43233
	5 NDBa(Ba)-GoGn	3.80512E-02	<u>0.611428</u>
	11 FH-GoGn	-3.62282E-02	<u>0.579619</u>
	6 pA-NPo(mm)	<u>0.575248</u>	0.180436
	9 ANB	0.483051	0.181425
	13 N-pA(mm)	<u>0.690603</u>	<u>0.693827</u>
	16 N-ANS(mm)	<u>0.661283</u>	<u>0.639291</u>
	17 ANS-Me(mm)	<u>0.96698</u>	<u>0.969362</u>
	15 N-pA:pA-Po x 100	-0.366837	<u>-0.740398</u>
	18 N-ANS:ANS-Me x 100	<u>-0.736495</u>	<u>-0.660804</u>

TABLE 34. CORRELATION COEFFICIENTS AMONG FACIAL PARAMETERS III (Continued)

Dependent Variable	Independent Variable	Group A	Group B
15 N-pA:pA-Po x 100	vs. 11 FH-GoGn	0.284095	<u>-0.501389</u>
	7 SNA	-0.472424	-6.46573E-03
	14 pA-Po (mm)	-0.366837	<u>-0.740398</u>
	17 ANS-Me (mm)	-0.194396	<u>-0.686172</u>
	18 N:ANS:ANS-Me x 100	<u>0.673699</u>	<u>0.866191</u>
16 N-ANS (mm)	vs. 3 FH-NPo	-0.269101	-0.462773
	4 NDBa (Ba)-PtGn	<u>-0.529534</u>	<u>-0.524173</u>
	8 SNB	-0.385113	<u>-0.527279</u>
	13 N-pA (mm)	<u>0.951282</u>	<u>0.956009</u>
	14 pA-Po (mm)	<u>0.661283</u>	<u>0.639291</u>
	17 ANS-Me (mm)	<u>0.743136</u>	<u>0.614612</u>
17 ANS-Me (mm)	vs. 4 NDBa (Ba)-PtGn	-0.338222	-0.478143
	5 NDBa (Ba)-GoGn	-2.58361E-02	<u>0.630919</u>
	11 FH-GoGn	-0.111955	<u>0.540693</u>
	6 pA-NPo (mm)	0.449058	0.208708
	13 N-pA (mm)	<u>0.794645</u>	<u>0.708293</u>
	16 N-ANS (mm)	<u>0.743136</u>	<u>0.614612</u>
	14 pA-Po (mm)	<u>0.96698</u>	<u>0.969362</u>
	15 N-pA:pA-Po x 100	-0.194396	<u>-0.686172</u>
	18 N-ANS:ANS-Me x 100	<u>-0.713459</u>	<u>-0.722251</u>

TABLE 34. CORRELATION COEFFICIENTS AMONG FACIAL PARAMETERS III (Continued)

Dependent Variable	Independent Variable	Group A	Group B
18 N-ANS:ANS-Me x 100 vs.	5 NDBa(Ba)-GoGn	0.319415	<u>-0.505282</u>
	14 pA-Po(mm)	<u>-0.736495</u>	<u>-0.660804</u>
	17 ANS-Me(mm)	<u>-0.713459</u>	<u>-0.722251</u>
	15 N-pA:pA-Po x 100	<u>0.673699</u>	<u>0.866191</u>

The number preceding each variable indicates the position of that variable within the correlation coefficient matrix.

The underlined correlation coefficients are statistically significant to at least the 0.05 confidence level.

See Appendix for critical values of the correlation coefficients.

## DISCUSSION

An analysis of facial form includes assessments of the orientation of the maxilla to the cranial base, the orientation of the mandible to the cranial base, the relationship of the maxilla to the mandible, the relationship of the mid-facial height to the lower facial height, as well as an assessment of the degree of facial asymmetry.

In this study, the measurement and statistical analysis of facial asymmetry parameters are not established. However, a detailed visual inspection of the 16 occipitalized skulls is undertaken, which indicates that 15 out of the 16 skulls appear to be symmetrical within acceptable standards. Only skull 0-2 is markedly asymmetrical in facial form. This observation is truly remarkable, considering the significant asymmetry of the atlanto-occipital fusion, rotations at the site of fusion, differences in thickness of the fused atlas in the superior-inferior dimension, and alterations in the base of the occipital bone. The concept that changes in facial morphology compensate for alterations at the atlanto-occipital junction, as stated by Dwight (1904) and List (1941), is only evident in occipitalized skull 0-2. The obliquity of the other occipitalized skulls may have been compensated by alterations in cervical vertebral orientation, caudad to the atlanto-occipital region, i.e., fusion of C<sub>2</sub> and C<sub>3</sub> or asymmetry of articulation and formation of these vertebrae. In some occipitalized skulls, asymmetrical fusion of the atlanto-occipital joints may have occurred after facial growth had completed.

While evaluating facial form, it is appropriate to compare relationships within the cranial base. The comparison of the basal angle, the length of the anterior cranial floor, the length of the clivus, and the ratio of

of these two lengths shows no significant statistical differences between the occipitalized skulls and the selected normal skulls. The basal angles of  $131.7^{\circ} \pm 7.0^{\circ}$  (occipitalized skulls) and  $131.1^{\circ} \pm 5.3^{\circ}$  (normal skulls) differ from an established norm of  $129^{\circ}$  (range: 114 - 144), claimed by Ricketts (1960 a), by only two degrees. The lengths of the anterior cranial floor and the clivus differ by less than a millimeter and less than two millimeters respectively between the two groups, the occipitalized skulls being smaller. The ratios of these lengths differ only by a value of two. It is noted that the variation of data within the cranial base measurements, as with most of the facial parameters, is greater among the occipitalized skull population, substantiated by larger standard deviations and coefficients of variation.

Four measurements are determined to evaluate the possibility of basilar impression. Those measurements are derived from established parameters, relating the tip of the odontoid process to a particular reference line. Since the available skull material does not have an intact cervical spinal column, the points Basion (Ba) or Derived Basion (DBa) are substituted for the tip of the odontoid process in these measurements. All four measurements denote significant statistical differences between Group A (occipitalized skulls) and Group B (normal skulls), strongly indicating an elevation of the base of skull among occipitalized skulls. Bull, Nixon, and Pratt (1955) stated that the mean value of Chamberlain's measurement is  $2.86 \text{ mm.} \pm 3.03 \text{ mm.}$  for normal skulls. From this study, the mean value, measuring the distance Basion or Derived Basion lies above the PNS-Op line, is  $1.7 \text{ mm.} \pm 1.6 \text{ mm.}$  for the normal skulls and  $5.8 \text{ mm.} \pm 3.5 \text{ mm.}$  for occipitalized skulls, a difference of 4.1 mm. Comparisons of the other measurements (Ba-ML(mm) with DBA-ML(mm) and Ba-DGL(mm) with DBa-DGL(mm)) show similar results. McRae (1971) stated that the atlanto-occipital joint interspace is  $11 \text{ mm.} \pm 4 \text{ mm.}$

inferior to the Digastric Line. In this study, the inferior aspect of the occipital condyle (OC) lies  $13.5 \text{ mm.} \pm 2.8 \text{ mm.}$  inferior to the Digastric Line for the normal skulls and  $6.4 \text{ mm.} \pm 3.6 \text{ mm.}$  inferior to DGL among the occipitalized skulls, a difference of  $7.1 \text{ mm.}$  All these comparisons are statistically significant to at least a 0.05 confidence level, Chamberlain's measurement and OC-DGL(mm) less than a 0.001 probability. There is a definite statistical difference between the two groups, showing elevation of the anterior rim of the foramen magnum among occipitalized skulls. It is unknown if this difference is significant on a clinical basis.

The orientation of the cranial base reference lines (N-Ba or NDBa, and S-N), used in facial cephalometric analyses, to Frankfort Horizontal shows no significant differences between the two groups, considering all 16 paired skulls. However, when the 12 paired adult skulls are compared alone, tendencies toward statistical significance are observed. For the sets of 12, the means of Ricketts' angle of cranial deflection are  $26.1^\circ \pm 3.9^\circ$  for the occipitalized skulls and  $28.2^\circ \pm 2.3^\circ$  for the normal skulls, compared to an established norm of  $27^\circ \pm 3^\circ$  (Rocky Mountain Data Systems, Inc.). The difference of  $2.1^\circ$  between the two groups is close to statistical significance, with a probability of 0.062 (Students "T" Test). The upward displacement of Derived Basion within the occipitalized skull population can account for this difference. This two-degree difference may require consideration, when evaluation of facial parameters using Huxley's line as a reference line is addressed. The comparison of S-N line to the Frankfort Horizontal reveals a difference of  $1.9^\circ$  between the two groups, evaluating the 12 paired adult skulls only, with a probability of 0.076. The means are  $7.3^\circ \pm 3.3^\circ$  and  $9.2^\circ \pm 2.8^\circ$  for Groups A and B respectively, compared to an established norm of  $9.8^\circ \pm 2.8^\circ$  (Moore, 1976). This observation tends to indicate that Sella

might be somewhat elevated in the occipitalized skull population, which could cause an alteration in angular measurements using S-N as a reference line.

There is a statistically significant difference in the orientation of the mandible between the two groups. The mandibles from occipitalized skulls appear to be positioned more posteriorly and inferiorly than their normal skull counterparts. The angular measurements FH-NPo and SNB determine the anterior-posterior orientation of the anterior mandible to the cranial base. The difference between the two groups is  $2.8^{\circ}$  for FH-NPo, significant to a 0.012 confidence level by one statistical test and less than 0.025 by the other. The means for the two groups are  $87.4^{\circ} \pm 3.9^{\circ}$  (Group A) and  $90.25^{\circ} \pm 2.9^{\circ}$  (Group B), compared to the established norm of  $90^{\circ} \pm 3^{\circ}$  (Rocky Mountain Data Systems, Inc.). The difference between the two groups for SNB is  $1.9^{\circ}$ , insignificant by one test but close to being significant by the other, with a probability of 0.075. The means are  $78.5^{\circ} \pm 4.4^{\circ}$  (occipitalized skulls) and  $80.4^{\circ} \pm 2.9^{\circ}$  (normal skulls), compared to an established norm of  $80^{\circ} \pm 4^{\circ}$  (Steiner, 1953; Hinds and Kent, 1972). Correcting for the SN-FH difference between the two groups, the mean for SNB within the occipitalized skull population would be approximately  $76.6^{\circ}$ , which is clearly statistically different from  $80.4^{\circ}$  for the normal population. Therefore, the mandible appears to be retruded in the occipitalized group of skulls.

The downward or inferior orientation of the mandible is evaluated by three mandibular plane angle measurements, each using a different reference line. All three measurements show statistically significant, or close to statistically significant, differences between the two groups. The difference of FH-GoGn is  $4.7^{\circ}$  between the two groups, Group A being larger, with a probability of 0.51 by one statistical test and less than 0.05 by the other. The means are  $26.1^{\circ} \pm 8.7^{\circ}$  for Group A and  $21.4^{\circ} \pm 5.4^{\circ}$  for Group B, compared

to an established norm of  $23^{\circ} \pm 4.5^{\circ}$  (Rocky Mountain Data Systems, Inc.). The difference of the second mandibular plane angle (SN-GoGn) is  $4.3^{\circ}$  between the two groups, with probabilities of 0.051 by one test and slightly greater than 0.05 by the other. The means for SN-GoGn are  $34.3^{\circ} \pm 8.25^{\circ}$  for Group A and  $30.0^{\circ} \pm 6.1^{\circ}$  for Group B, compared to the established norms of  $32^{\circ}$  (Steiner, 1953) and  $35.5^{\circ} \pm 5^{\circ}$  (Hinds and Kent, 1972). If the mean in Group A is corrected for differences of NS-FH between the two groups, then the mean for SN-GoGn in occipitalized skulls would be approximately  $36.2^{\circ}$ , which is certainly statistically different from the mean for the normal skull population. The difference of the third mandibular plane angle (NDBa-GoGn or NBa-GoGn) between the two groups is  $3.6^{\circ}$ , which is statistically insignificant by one test and close to being significant by the other, with a probability of 0.083. The mean of NDBa-GoGn in Group A is  $52.9^{\circ} \pm 8.3^{\circ}$ , compared to the mean of NBa-GoGn in Group B of  $49.25^{\circ} \pm 5.9^{\circ}$ . If the mean in Group A is adjusted for the difference in the NDBa-FH/NBa-FH relationship, then the mean for the occipitalized skulls would be approximately  $55^{\circ}$ , demonstrating a statistically significant difference from the mean for normal skulls. These three mandibular plane angle measurements suggest that the mandibular plane is steeper among occipitalized skulls, reflecting a more obtuse gonial angle and/or an increased downward projection of the chin.

Ricketts' angle of facial axis, NDBa-PtGn in the occipitalized skulls and NBa-PtGn in the normal skulls, measures the vector of downward and forward growth of the mandible, the chin in particular, in relation to the cranial base. In essence, it is a composite measurement of the anterior-posterior relationships of the mandible and its superior-inferior orientation. It is felt that the lower face, especially the chin, grows along this PtGn line to maturity. The difference of NDBa-PtGn or NBa-PtGn between the two groups

is  $3.1^\circ$ , which is statistically significant by one test, with a probability of 0.04, and marginally significant by the other test, with a probability very slightly greater than 0.05. The means are  $88.8^\circ \pm 5.6^\circ$  for Group A and  $91.9^\circ \pm 3.8^\circ$  for Group B, compared to the established norm of  $90^\circ \pm 3.5^\circ$  (Rocky Mountain Data Systems, Inc.). If the NDBa line is adjusted to correct the difference between the groups of the NDBa-FH/NBa-FH parameter, then the mean of the NDBa-PtGn angle would be approximately  $86.7^\circ$ , enhancing the statistical significance of the difference of this measurement between the two groups. Thus, it appears that mandibles of occipitalized skulls are oriented more posteriorly and inferiorly in relation to the cranial base and exhibit an increased mandibular plane angle, when compared to mandibles of normal skulls.

The orientation of the maxilla to the cranial base in the anterior-posterior direction is assessed only by the measurement SNA. The measurement pA-NPo(mm) can be an effective alternative in assessing anterior-posterior maxillary position, if the NPo line is oriented properly. However, this is not the case among occipitalized skulls. To assess the anterior-posterior position properly, the distance between Point A and a "Frankfort Vertical" line, a line originating from Nasion, perpendicular to the Frankfort Horizontal plane, should be evaluated. This measurement is not recorded in this study. The difference of SNA between the two groups is  $0.06^\circ$ , totally insignificant by both statistical tests. The means are  $84.625^\circ \pm 3.9^\circ$  for occipitalized skulls and  $84.6875^\circ \pm 4.0^\circ$  for normal skulls, compared to the established norm of  $82^\circ \pm 3^\circ$  (Steiner, 1953; Hinds and Kent, 1972). Even if adjustments are made in the S-N line of the occipitalized group to correct the difference in the SN-FH angle between the two groups, the difference of SNA between the groups would not be statistically significant. Therefore, there

is no statistical difference in the orientation of the maxilla to the cranial base in an anterior-posterior direction between occipitalized and normal skulls.

The relationship of the mandible to the maxilla in an anterior-posterior dimension is assessed by two measurements: ANB and pA-NPo(mm). These values are positive numbers when the line NA and point A are anterior to lines NB and NPo respectively. The difference of ANB between the two groups is  $2.1^{\circ}$ , which is statistically significant by both tests, with probabilities of 0.05 and 0.028. The means are  $6.1^{\circ} \pm 2.7^{\circ}$  for Group A and  $4.2^{\circ} \pm 2.7^{\circ}$  for Group B, compared to the established norm of  $2^{\circ} \pm 2^{\circ}$  (Steiner, 1953; Hinds and Kent, 1972). The difference of pA-NPo(mm) between the two groups is 2.4 mm., statistically significant by both tests, with probabilities of 0.008 and less than 0.025. The means are 5.1 mm.  $\pm$  2.8 mm. for the occipitalized group and 2.7 mm.  $\pm$  2.7 mm. for the normal group of skulls, compared to the established norm of 0 mm.  $\pm$  2 mm. (Rocky Mountain Data Systems, Inc.). These comparisons indicate that there are significant statistical differences between the occipitalized and normal skull populations, regarding the relationship of the mandible to the maxilla in an anterior-posterior dimension. Since it has been shown that the position of the maxilla is essentially the same in both groups, then the differences of ANB and pA-NPo(mm) between the two groups are factors of the mandibular anterior-posterior orientation. This observation gives further support to the concept that the mandible has a retruded orientation in respect to the maxilla and the cranial base among occipitalized skulls.

It is noted on several occasions that the mean of a given facial measurement within the normal skull population differs considerably from the established norm, as fostered by Steiner, Ricketts and others, e.g., SNA, ANB, pA-NPo(mm). Racial and ethnic factors can account for these variations.

The skulls used in this study were imported from India, exhibiting features characteristic of various Indian sects, while the established norms were obtained from the Caucasian race, primarily of European stock. It appears that the Indian skulls tend to be slightly maxillary protrusive as compared to the established norms. This observation is based upon increased SNA and ANB angles and a larger pA-NPo(mm) measurement among the Indian skulls, while SNB and FH-NPo angles remain unchanged. Because of potential differences between Indian skulls and those used to establish the published norms, the selection process of obtaining normal Indian skulls was used, instead of relating the occipitalized skulls to the established normal values.

The relationship of the mid-facial height to the lower facial height is assessed by the ratios  $N-pA:pA-Po \times 100$  and  $N-ANS:ANS-Me \times 100$ . The comparison of these ratios is more important than comparing mid-facial heights and lower facial heights by themselves, because the ratios discount variation in total size of the skulls and emphasize proportional relationships. However, data assessing these individual heights are presented also. The difference of the ratio  $N-pA:pA-Po \times 100$  is a value of 3.6 between the two groups, which is not statistically significant by either test. The means are  $106.6 \pm 8.5$  for the occipitalized skulls and  $103.0 \pm 8.0$  for the normal skulls, compared to the established norm of 8:7 (Hinds and Kent, 1972), which presented as a decimal and multiplied by 100 is 114. The difference of the ratio  $N-ANS:ANS-Me \times 100$  between the two groups is 1.8, which is even less significant than the other ratio. The means are  $78.2 \pm 6.5$  for Group A and  $76.4 \pm 6.4$  for Group B, compared to the established norm of 7:9 (Hinds and Kent, 1972), which is 77.8 when presented as a decimal and multiplied by 100. Therefore, there is no statistical difference of the mid-facial height to lower facial height relationships between the occipitalized and normal skull

populations. The comparisons of the linear mid-facial heights (N-pA(mm) and N-ANS(mm)) and the lower facial heights (pA-Po(mm) and ANS-Me(mm)) between groups also indicate no statistically significant differences. Therefore, occipitalization of the atlas has no apparent effect on facial height.

A special comment must be made regarding measurements using the point Pseudo-Basion (PBa), the inferior mid-sagittal point on the anterior rim of the atlas. The means of those measurements containing PBa differ drastically from the means of the similar parameters containing DBa (Group A) and Ba (Group B). On several occasions, the difference is greater than ten degrees or millimeters; all comparisons have probabilities of less than 0.001 by both tests. The importance of this observation concerns the erroneous cephalometric analysis data obtained where Pseudo-Basion is misinterpreted as Basion, when the anterior arch of the atlas is completely fused or assimilated into the basi-occiput. The evaluation of the facial axis depicts a good example of this erroneous information. The mean for NPBa-PtGn is  $81.9^{\circ} \pm 6.3^{\circ}$ , compared to  $88.8^{\circ} \pm 5.6^{\circ}$  for NDBa-PtGn (Group A) and  $91.9^{\circ} \pm 3.8^{\circ}$  for NBA-PtGn (Group B). Pseudo-Basion, therefore, is a separate, distinct data point on skulls exhibiting occipitalization of the atlas. The failure to recognize this anomalous fusion can lead to misinterpretation of cephalometric analysis data.

It has been established that statistical differences exist between the occipitalized skull population and the group of normal skulls. The differences appear in the orientation of the mandible to the cranial base and to the maxilla in an anterior-posterior dimension. The mandibular plane angles and facial axis are affected as well. Statistical differences are not present in the orientation of the maxilla to the cranial base and in facial height relationships. Significant statistical differences are noted in measurements, relating a point at, or adjacent to, the anterior rim of the foramen magnum to

certain reference lines, which are suggestive of basilar impression. The differential significance between the two groups is very tentative concerning the length of the clivus. The differences involving the orientation of the cephalometric reference lines (SN and NBa or NDBa) to the Frankfort Horizontal are somewhat tentative, but are close to being statistically significant between the two groups. There are no statistical differences between the occipitalized and normal skulls regarding basal angle, length of the anterior cranial floor, ratio of the length of the clivus to the anterior cranial floor, and the length and breadth of the cranium; the latter two measurements were used in the selection process for determining the normal skull population.

It is important to determine if any of these facial analysis measurements are directly related to specific alterations or variations at the base of the skull. The most significant relationships are those that correlate facial measurements with basilar impression-related parameters and the length of the clivus. These relationships, however, do not really correlate occipitalization of the atlas with the facial parameters directly, but correlate the basilar impression tendencies of the occipitalized skulls with facial morphology. Other effects of atlanto-occipitalization, besides tendencies toward basilar impression, involve the orientation of the skull on top of the cervical spine in all planes and the degree of assimilation or incorporation of the atlas into the basi-occiput. These effects are not included in this study.

Using a correlation analysis, relationships or lack of relationships among various cranial and facial measurements can be determined. Generally, cranial measurements tend to correlate significantly with other cranial measurements, and facial parameters tend to correlate with other facial

parameters. However, few facial measurements correlate significantly with the cranial parameters. Therefore, as a general rule, the cited facial and cranial measurements tend to be independent of one another. Many of the statistically significant relationships are the direct result of correlating sizes of different parts of the skull with one another, primarily linear lengths and distances. The statistical correlation analysis is performed for the occipitalized and normal skull populations independently. The correlation coefficients must be statistically significant in both groups, or at least in the occipitalized group (Group A), to have a truly meaningful, significant relationship.

The basilar impression-related measurements and the length of the clivus significantly correlate with the cranial length among the normal skulls, but not among the occipitalized skulls. This observation indicates that the orderly pattern of growth, which occurs among normal skulls, is disturbed in the basilar region of occipitalized skulls. On the other hand, the length of the anterior cranial floor has statistically significant correlations with the cranial length in both populations, indicating the linear growth of the anterior cranium is not influenced by the occipitalization process. The basilar impression-related measurements also significantly correlate with the length of the clivus among occipitalized skulls, showing the impact that the length of the clivus has on these measurements. This relationship is only marginal within the normal skull population. Other compensations must occur in the cranial base of normal skulls to affect this correlation. The relationships between the basilar impression-related measurements and the ratio of the length of the clivus to the length of the anterior cranial floor behave in a similar fashion as those measurements related to the length of the clivus alone. Significant correlations exist

among occipitalized skulls, but are insignificant among the normal skulls. The variability of the length of the clivus within the occipitalized skull population impacts on this ratio.

The basal angle is not influenced by any of the cited cranial/basilar measurements in either group. The basilar impression-related parameters, the length of the clivus, the length of the anterior cranial floor, and cranial length and breadth do not impact upon the basal angle. The orientation of the Sella-Nasion line to the Frankfort Horizontal (SN-FH) does not correlate significantly with any of the basilar impression-related measurements in either group. There are some minor statistical tendencies between the orientation of the Sella-Nasion line and the cranial length and the length of the clivus in the normal group, but these tendencies are negated within the occipitalized population. The relationships between the SN-FH angle and the basal angle show a strongly significant correlation within the occipitalized skull population and a strong tendency among normal skulls. It is surprising that this relationship is not more statistically significant in the normal group. The strong correlation is due to the fact that both angular relationships share a common line (S-N). As a result, SN-FH angle is not affected by the basilar impression elements of the occipitalization process and is dependent only on the basal angle, which in itself is not affected by the other basilar parameters.

Ricketts' angle of cranial deflection, the relationship of Huxley's line to the Frankfort Horizontal, correlates significantly with the basilar impression-related measurements, the length of the clivus and the ratio between the length of the clivus and the length of the anterior cranial floor within the occipitalized skull population. Therefore, the orientation of Huxley's line appears to be directly affected by the degree of basilar

impression within the occipitalized skull population. This influential relationship can be appreciated, since all of these measurements anatomically involve a common element, Derived Basion, the inferior mid-line point of the clivus. Among the normal skulls, the angle of cranial deflection correlates significantly only with two of the three basilar impression-related measurements. The parameter measuring the distance between Basion and Chamberlain's line absolutely does not correlate with the angle of cranial deflection within the normal skull population. This incongruity is related to variations in the reference line, specifically the orientation of the Posterior Nasal Spine as related to the posterior facial height.

The orientation of the mandible in the anterior-posterior direction is not significantly dependent upon the cited cranial/basilar measurements. The angle SNB does not correlate with the basilar impression-related parameters, length of the clivus or any other cranial relationships in either group, except for the orientation of the Sella-Nasion line in respect to the Frankfort Horizontal. The SN-FH relationship significantly correlates with SNB in both groups, which is a function of sharing the same line (S-N). The Nasion-Pogonion line as it relates to the Frankfort Horizontal (FH-NPo) correlates significantly with the length of the cranium and two of the three basilar impression-related measurements in the normal skull population. The third relationship between FH-NPo and the basilar impression-related measurement shows a mild suggestion toward correlation. These four correlative tendencies are not statistically significant within the occipitalized skull group. Therefore, occipitalization of the atlas tends to disrupt the normal pattern of these relationships; however, the element of basilar impression does not influence the FH-NPo angle. Consequently, the anterior-posterior orientation of the mandible is not affected directly by alterations in

basilar impression-related measurements, the length of the clivus or other cited cranial parameters.

The mandibular plane angles, which measure the superior-inferior orientation of the mandible, are not affected by the cited basilar/cranial parameters. The angles of FH-GoGn and NBa-GoGn (or NDBa-GoGn) show no significant correlations with the cranial length and breadth, the length of the clivus, the length of the anterior cranial floor, basal angle, basilar impression-related measurements or the cephalometric reference lines, as related to the Frankfort Horizontal, in either group. Consequently, the elements of basilar impression and other cited cranial/basilar measurements do not influence the superior-inferior orientation of the mandible.

Ricketts' facial axis, a composite measurement of the anterior-posterior and superior-inferior vectors of mandibular orientation to the cranium, does not correlate with the cited cranial/basilar parameters in either skull population, except in a couple of minor instances. The facial axis correlates statistically with the cranial breadth among occipitalized skulls only. This correlation appears to be meaningless. The facial axis also correlates significantly with the angle of cranial deflection, the relationship between Huxley's line and the Frankfort Horizontal, in both groups. Since both measurements share a common line (N-Ba or N-DBa), changes in one measurement tend to affect the other. The facial axis also tends to correlate, although not significantly, with the basal angle in the normal skull population, but not among the occipitalized skulls. The facial axis does not correlate with any of the basilar impression-related measurements or the length of the clivus in either group. Considering previous relationships involving the orientation of the mandible, the elements of basilar impression

or other cited cranial/basilar measurements do not influence the orientation of the mandible in either the anterior-posterior or superior-inferior direction.

The orientation of the maxilla to the cranial base in an anterior-posterior direction is not affected by any of the cited cranial/basilar parameters in either group. SNA correlates significantly with the SN-FH relationship in the occipitalized skull group, but exhibits only a very tentative correlation, not statistically significant, with SN-FH in the normal skull group. It is surprising that the SNA/SN-FH relationship is not strong among normal skulls, since the Sella-Nasion is shared by these two angles. SNA does not correlate significantly with the basilar impression-related measurements, the length of the clivus, the length of the anterior cranial floor, or the length and breadth of the cranium. Therefore, the elements of basilar impression and the other cited basilar measurements do not influence or impact upon the orientation of the maxilla in an anterior-posterior direction.

The relationship of the mandible to the maxilla in an anterior-posterior direction has only one significant correlation among cranial/basilar parameters. ANB correlates significantly with the distance Basion to Chamberlain's line in the normal skull population, but not in the occipitalized group. Correlations between ANB and the other two basilar impression-related measurements are insignificant in both groups. The significant correlation between ANB and Ba-PNSOp(mm) among normal skulls must be related to the orientation of the PNS-Op reference line, the posterior facial height in particular, which influences the Posterior Nasal Spine. This relationship is negated by the variation of Derived Basion in the occipitalized skull population. ANB tends to correlate with the length of the clivus among normal skulls, but shows absolutely no correlation with the length of the clivus

among occipitalized skulls. The measurement pA-NPo(mm) has a similar arrangement with the length of the clivus. The basilar impression-related parameters do not correlate with pA-NPo(mm) in either group. Therefore, the elements of basilar impression, the length of the clivus, and other cranial parameters do not impact upon, or cause, the altered anterior-posterior relationship between the maxilla and mandible, noted in the occipitalized skull population.

The analysis of facial height indicates several significant correlations with cranial/basilar measurements within the normal skull population, but few within the occipitalized skull population. The mid-facial height measurements (N-pA(mm) and N-ANS(mm)) both correlate significantly with the cranial breadth, the length of the clivus, the length of the anterior cranial floor, and the relationship between Basion and Chamberlain's line among normal skulls. N-pA(mm) also correlates significantly with the cranial length within the normal skull population, while the correlative relationship between N-ANS(mm) and the cranial length is close to being significant at the 0.05 confidence level. N-ANS(mm) also correlates with the relationship between Basion and the Mastoid Line among normal skulls, while N-pA(mm) does not correlate significantly with this relationship, but shows a tendency to correlate. Since those relationships involve linear measurements only, these parameters should correlate with one another to maintain proper proportional relationships. In contrast, all of the above correlations within the occipitalized skull group are statistically insignificant, except for the correlation of both mid-facial height measurements with the cranial breadth. The basilar impression-related parameters, the length of the clivus, and the cranial length no longer correlate with the mid-facial height among occipitalized skulls. If these basilar parameters are to influence the mid-facial height measurements, they must show their effect within the occipitalized

skull population, where the basilar elements are more variable. This is not the case; therefore, the height of the mid-face is formed independently of cranial/basilar parameters.

Many of the same things can be said about the lower facial height and its relationships with the cranial/basilar measurements. The lower facial height measurements pA-Po(mm) and ANS-Me(mm) correlate with the cranial length, the length of the anterior cranial floor, the length of the clivus, and the relationship between Basion and Chamberlain's line in the normal skull population. The only correlations that remain intact within the occipitalized group are the lower facial heights with the length of the clivus. The lower facial heights also correlate significantly with the cranial breadth within the occipitalized skull population, instead of the cranial length. Therefore, the length of the clivus is influential in establishing the lower facial height, but the basilar impression measurements do not impact on lower face development.

The mid-facial height to lower facial height ratios, which are more important in detecting facial disharmonies, have only one statistically significant correlation with the cranial/basilar measurements. The ratio  $N-ANS:ANS-Me \times 100$  significantly correlates with the length of the clivus within the occipitalized skull population. This correlation indicates the significant impact the length of the clivus has on the lower facial height. This same correlation among normal skulls is statistically insignificant. The relationship between the other facial height ratio and the length of the clivus is insignificant in both groups.  $N-pA:pA-Po \times 100$  has close to a significant correlation with the length of the anterior floor among normal skulls only. This relationship is not present regarding the other facial

height ratio. The basilar impression-related measurements appear to have no influence on the facial heights and their ratios.

Many of the correlations between one facial parameter and another reflect anatomic and geometric interrelations among these parameters. Many of them are logical and intuitive. A detailed discussion of these interrelations and correlations is not presented here. Refer to the Results section and Tables 29, 31, and 34 for specifics regarding correlations among facial parameters. It is interesting to note that Ricketts' facial axis and SNB correlate with the mid-facial height parameters in an inverse fashion, particularly among normal skulls. Also, Ricketts' facial depth measurement (FH-NPo) tends to correlate with the mid-facial height parameters in a similar manner, although these relationships are not statistically significant. These relationships indicate that the mandible becomes more retruded and inferiorly oriented as the mid-face increases. This observation reflects the pattern of the "long face" syndrome, also called adenoid facies.

Other interesting relationships exist involving pA-NPo(mm) and ANB with SNA, SNB and FH-NPo. In the normal skull population the ANB angle and the distance point A to the NPo line are more dependent upon the orientation of the maxilla to the cranial base (SNA), while these measurements are more dependent upon the orientation of the mandible in the anterior-posterior direction (SNB, FH-NPo) within the occipitalized skull population. This observation indicates the effect the altered orientation of the mandible has on the measurements, relating the mandible to the maxilla, within the occipitalized skull population.

To summarize this section, the following observations are noted. There are strong statistical differences between the two skull groups,

suggesting the presence of basilar impression within the occipitalized group. There are somewhat tentative differences between the two skull groups involving the length of the clivus and relationships of Huxley's line and the Sella-Nasion line to the Frankfort Horizontal. The orientation of the mandible in an anterior-posterior direction, as well as a superior-inferior direction, is statistically different between occipitalized and normal skulls. In addition, the relationship of the maxilla to the mandible is different between the two groups. The orientation of the maxilla to the cranial base in an anterior-posterior direction and the relationship of facial heights show no statistical differences between the groups.

The correlation analysis indicates that the length of the clivus is statistically correlated with the measurements, suggestive of basilar impression within the occipitalized skull group. The angle of cranial deflection (NBa-FH or NDBa-FH) is directly affected by the basilar impression relationships and the length of the clivus in occipitalized skulls. The element of basilar impression does not correlate or impact upon the orientation of the mandible to the cranial base, the orientation of the maxilla to the cranial base, the relationship between the mandible and maxilla, and the facial height relationships. The length of the clivus statistically correlates with the lower facial height parameters.

The degree of basilar impression associated with occipitalization of the atlas does not influence facial morphology. The altered orientation of the mandible and its relationship to the maxilla may be caused by other manifestations, associated with the atlanto-occipitalization, which are not addressed in this study. Other potential causes are the degree of assimilation of the atlas, the amount of anterior displacement of the atlas on the axis or beneath the cranial base, the degree of hyperextension of the skull

upon the spinal column, and the asymmetry of the lateral masses of the fused atlas, or a combination of these alterations at the base of the skull and proximal cervical vertebrae and their orientations.

Finally, a hypothesis is proposed which may account for the alterations in facial morphology, the mandible in particular, observed in occipitalized skulls. In accordance with the compensation theories, fostered by Dwight (1904), List (1941) and others, the cited mandibular retrusion and its associated orientations can be considered compensations for the noted cranio-cervical hyperextension, resulting from the fusion of the atlas to the basi-occiput. These facial compensations in a hyperextended skull allow the frontal plane of the face to remain in a relatively normal and upright posture.

## SUMMARY

An attempt was made to determine if facial form or morphology is affected or altered by the presence of the anomaly at the cranio-vertebral junction, called occipitalization of the atlas. Sixteen dried skulls bearing this anomaly and 16 selected normal skulls, chosen on the basis of comparable cranial indices, cranial breadth and cranial length, were subjected to radiographic cranial and cephalometric analyses. Measurements were obtained from the right lateral and posterior-anterior cephalometric radiographs and submitted to statistical analysis. Basic statistical data for each measurement from the group of occipitalized skulls and from the group of selected normal skulls were calculated. The data obtained from the occipitalized group were compared with the set of data from the normal skulls, using the Students "T" Test and the Mann-Whitney "U" Test, to determine if differences were statistically significant between the two groups. A correlation analysis was performed for each group, which provided correlation coefficients between two given measurements within the same group. The purpose of the correlation analysis was to determine if the obtained facial measurements correlated or were influenced statistically by alterations in the cranial base.

In addition, detailed descriptions of the anomalous atlanto-occipital fusions and their associated abnormalities in the basi-occiput were discussed for each occipitalized skull used in this study. Attention was directed toward the observation of gross facial asymmetry. Measurements regarding facial asymmetry were not obtained from these skulls; therefore, statistical analyses concerning facial asymmetry parameters are not available.

The results indicate that there are statistical differences in the orientation of the mandible to the cranial base and in the relationship

between the maxilla and the mandible between the two groups. The orientation of the mandible to the cranial base within the occipitalized skull population is more retruded and inferiorly projected than among normal skulls. The mandible is retruded also in relation to the maxilla among occipitalized skulls. There are no significant statistical differences in the orientation of the maxilla to the cranial base or in facial height relationships between the two groups. Only one skull out of the 16 occipitalized skulls exhibits marked facial asymmetry by gross inspection. The correlation analysis indicates that the cited cranial/basilar measurements do not correlate or influence the facial analysis parameters; therefore, the development of facial morphology occurs independently of the cited cranial/basilar observations, which basically measure elements of basilar impression. However, the elements of basilar impression and the length of the clivus significantly influence the orientation of Huxley's line to the Frankfort Horizontal, and the length of the clivus correlates significantly with the lower facial height parameters.

## CONCLUSIONS

1. These occipitalized skulls possess elements of basilar impression, which may or may not be clinically significant.
2. These occipitalized skulls tend to have shortened clivuses, although not of statistical significance.
3. The elements of basilar impression and shortened clivus influence the orientation of Huxley's line with the Frankfort Horizontal.
4. The orientation of Huxley's line and the Sella-Nasion line to the Frankfort Horizontal tends to be altered slightly among occipitalized skulls.
5. These occipitalized skulls have mandibles which are retruded and projected inferiorly in relation to the cranial base, when compared to mandibles of normal skulls.
6. The orientation of the maxilla to the cranial base is unaltered in these occipitalized skulls.
7. The increased anterior-posterior distance between the maxilla and mandible is caused by the retruded mandible in these occipitalized skulls.
8. The facial height relationships remain unaltered in these occipitalized skulls.
9. The misinterpretation of Pseudo-Basion for Derived Basion produces very erroneous data in those measurements where Basion is an integral part.
10. The basilar impression element, associated with occipitalization of the atlas, does not influence facial form, although the length of the clivus correlates significantly with the lower facial height.

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APPENDIX

## INDIVIDUAL DATA POINTS: EXPERIMENTAL GROUP A - OCCIPITALIZED SKULLS

Measurements	0-1	0-2	0-3	0-5	0-6	0-9	0-10	0-11	0-12	0-13	0-17	0-18	0-4	0-14	0-15	0-16
C.I.	71.6	83.4	80.1	69.4	83.85	69.7	75.3	79.5	80.0	75.9	68.3	77.2	73.05	75.1	65.3	74.4
N-S-DBa	141°	127°	148°	121°	131°	127°	123°	129°	128°	134°	129°	138°	129°	140°	131°	131°
N-S-PBa	126°	-	129°	110°	117°	117°	118°	116°	115°	122°	117°	129°	117°	134°	117°	121°
NDBa-FH	21°	19°	25°	28°	29°	26°	26°	33°	25°	23°	28°	30°	26°	32°	26°	31°
NPBa-FH	29°	-	34°	35°	37°	32°	31°	43°	35°	31°	38°	35°	34°	35°	34°	38°
FH-NPo	92°	77°	90°	88°	91°	87°	89°	86°	81°	87°	91°	90°	87°	86°	86°	90°
NDBa-PtGn	100°	85°	94°	87°	89°	92°	93°	79°	80°	92°	92°	87°	92°	81°	91°	87°
NPBa-PtGn	93°	-	86°	79°	81°	88°	88°	69°	70°	85°	82°	82°	84°	78°	83°	81°
NDBa-CoGn	43°	70°	37°	53°	52°	43°	47°	62°	62°	49°	50°	55°	56°	58°	51°	58°
NPBa-CoGn	50°	-	45°	60°	59°	48°	52°	72°	72°	56°	60°	60°	64°	62°	59°	64°
pA-NPo (mm)	6	8	8	2	1	2	4	11	9	4	4	6	4	5	5	3
SNA	91°	85°	85°	84°	87°	85°	88°	87°	83°	86°	87°	83°	85°	73°	84°	81°
SNB	84°	75°	76°	81°	85°	81°	82°	75°	75°	81°	82°	76°	81°	68°	77°	77°
ANB	7°	10°	9°	3°	2°	4°	6°	12°	8°	5°	5°	7°	4°	5°	7°	4°
SN-FH	8°	2°	13°	6°	6°	5°	5°	10°	6°	6°	8°	13°	6°	18°	8°	12°

## INDIVIDUAL DATA POINTS: EXPERIMENTAL GROUP A - OCCIPITALIZED SKULLS (Continued)

Measurements	0-1	0-2	0-3	0-5	0-6	0-9	0-10	0-11	0-12	0-13	0-17	0-18	0-4	0-14	0-15	0-16
SN-GoGn	29°	52°	24°	31°	28°	22°	26°	40°	44°	31°	31°	39°	36°	45°	33°	38°
FH-GoGn	21°	50°	11°	25°	22°	17°	21°	30°	38°	25°	23°	26°	30°	27°	25°	26°
DBa-ML(mm)	18	18	15	9	3	11	6	1	19	13	0	0	3	14	1	1
PBa-ML(mm)	6	-	2	-3	-12	2	-4	-15	3	5	-11	-10	-8	6	-9	-7
N-pA(mm)	49	54	57	58	51	55	51	55	66	49	58	61	50	61	46	47
pA-Po(mm)	52	46	54	53	44	49	46	60	57	49	57	60	46	51	47	46
N-pA:pA-Po																
x 100	94.2	117	106	109	116	112	111	91.7	116	100	102	102	109	120	97.9	102
N-ANS(mm)	45	50	52	54	48	48	48	50	58	44	53	53	45	52	45	44
ANS-Me(mm)	62	54	69	67	56	64	55	73	74	60	72	77	57	65	56	55
N-ANS:ANS-Me																
x 100	72.6	92.6	75.4	80.6	85.7	75.0	87.3	68.5	78.4	73.3	73.6	68.8	78.9	80.0	80.4	80.0
S-DBa(mm)	39	34	42	42	46	48	39	50	42	39	47	51	44	37	43	41
S-N(mm)	69	61	70	68	58	71	76	62	70	61	74	75	65	66	72	62
S-DBa:S-N																
x 100	56.5	55.7	60.0	61.8	79.3	67.6	51.3	80.6	60.0	63.9	63.5	68.0	67.7	56.1	59.7	66.1

## INDIVIDUAL DATA POINTS: EXPERIMENTAL GROUP A - OCCIPITALIZED SKULLS (Continued)

Measurements	0-1	0-2	0-3	0-5	0-6	0-9	0-10	0-11	0-12	0-13	0-17	0-18	0-4	0-14	0-15	0-16
DBa-PNSOp (mm)	9	10	9	11	4	5	4	0	8	8	2	0	4	9	6	4
DBa-DGL (mm)	-4	-6	-4	-2	5	3	0	10	-7	-1	6	6	4	-8	10	3
PBa-DGL (mm)	5	-	9	9	20	12	10	26	9	4	17	16	15	0	20	12
OC-DGL (mm)	1	6	4	3	7	8	3	12	3	2	11	10	8	5	12	8
CrB(cm)	12.6	13.1	13.3	12.7	13.5	12.2	12.5	13.2	14.0	12.6	12.7	14.2	12.2	13.3	12.6	12.8
CrL(cm)	17.6	15.7	16.6	18.3	16.1	17.5	16.6	16.6	17.5	16.6	18.6	18.4	16.7	17.7	19.3	17.2

Skulls 0-4, 0-14, 0-15, and 0-16 are adolescent skulls; the other 12 are adult skulls.

Derived Basion (DBa) = the estimated point of anatomical Basion.

Pseudo-Basion (PBa) = the inferior mid-line point on the anterior arch of the first cervical vertebra.

CrB(cm) = the greatest breadth of the cranium, measured by anthropometric calipers.

CrL(cm) = the greatest length in the mid-line of the cranium, measured by anthropometric calipers.

The values of DBa-ML(mm), PBa-ML(mm), and DBa-PNSOp(mm) are positive, when DBa or PBa is cephalad to the respective reference line.

The values of DBa-DGL(mm), PBa-DGL(mm), and OC-DGL(mm) are positive, when DBa, PBa or OC is caudad to the reference line, DGL.

The values of pA-NPo(mm) and ANB are positive, when point A or the NA line is anterior to the lines NPo and NB respectively.

## INDIVIDUAL DATA POINTS: CONTROL GROUP B - NORMAL SKULLS

Measurements	N-11	C.I.	C.I.	C.I.	C.I.	C.I.	C.I.	C.I.	C.I.	C.I.	N-19	C.I.	C.I.	Y-7		
C.I.	71.8	85.6	80.1	69.6	81.4	69.9	73.15	78.6	81.0	75.9	69.9	76.2	73.3	75.4	66.1	74.4
N-S-Ba	125°	141°	135°	128°	134°	123°	134°	121°	133°	135°	128°	135°	134°	133°	132°	127°
NBa-FH	24°	27°	25°	27°	30°	30°	29°	32°	27°	30°	29°	28°	27°	25°	22°	28°
FH-NPo	90°	94°	88°	86°	89°	91°	94°	91°	92°	94°	91°	88°	93°	91°	87°	85°
NBa-PtGn	97°	95°	90°	90°	89°	90°	94°	85°	93°	94°	90°	89°	98°	95°	95°	86°
NBa-GoGn	40°	50°	55°	48°	54°	53°	46°	50°	43°	44°	50°	59°	40°	53°	45°	58°
pA-NPo(mm)	1	2	1	0	2	5	4	4	4	3	6	6	0	-4	6	3
SNA	88°	85°	82°	79°	78°	87°	87°	89°	86°	84°	90°	84°	85°	79°	91°	81°
SNB	85°	82°	80°	76°	75°	81°	81°	82°	80°	80°	82°	77°	84°	81°	84°	77°
ANB	3°	3°	2°	3°	3°	6°	6°	7°	6°	4°	8°	7°	1°	-2°	7°	4°
SN-FH	3°	11°	7°	8°	12°	9°	11°	7°	10°	13°	8°	11°	8°	8°	3°	8°
SN-CoGn	19°	35°	37°	29°	37°	31°	28°	26°	26°	27°	28°	37°	21°	36°	25°	38°
FH-GoGn	16°	23°	30°	21°	25°	22°	17°	19°	16°	14°	20°	26°	13°	28°	22°	30°
Ba-ML(mm)	2	-3	6	11	7	-1	4	3	10	0	4	3	3	10	14	6
N-pA(mm)	48	46	53	55	57	50	49	55	55	54	57	58	43	52	54	53
pA-Po(mm)	42	45	53	50	55	56	47	53	49	49	56	57	40	61	58	49

INDIVIDUAL DATA POINTS: CONTROL GROUP B - NORMAL SKULLS (Continued)

Measurements	N-11	C.I.	N-19	C.I.	C.I.	Y-7										
	143	117	125	126	140	107	101	103	118	144	106	123	132			
N-pA:pA-Po																
x 100	114	102	100	110	104	89.3	104	104	112	110	102	102	108	85.2	93.1	108
N-ANS(mm)	45	42	49	49	54	44	44	50	51	50	51	52	41	48	51	48
ANS-Me(mm)	53	57	64	62	65	68	60	68	62	60	69	73	49	75	68	60
N-ANS:ANS-Me																
x 100	84.9	73.7	76.6	79.0	83.1	64.7	73.3	73.5	82.3	83.3	73.9	71.2	83.7	64.0	75.0	80.0
S-Ba(mm)	44	40	46	43	45	44	42	48	43	42	49	47	43	44	50	42
S-N(mm)	68	61	66	67	71	72	64	67	72	68	70	71	60	75	74	65
S-Ba:S-N																
x 100	64.7	65.6	69.7	64.2	63.4	61.1	65.6	71.6	59.7	61.8	70.0	66.2	71.7	58.7	67.6	64.6
Ba-PNSOp(mm)	1	0	1	5	2	2	2	2	2	0	4	3	-1	1	3	0
Ba-DGL(mm)	4	8	5	2	4	6	5	6	2	6	6	4	6	3	2	2
OC-DGL(mm)	14	18	13	14	14	14	13	17	11	16	15	14	15	12	8	8
CrB(cm)	12.5	13.1	13.3	12.6	13.6	12.3	12.4	13.2	14.1	12.6	12.8	13.8	12.1	13.5	12.5	12.8
CrL(cm)	17.4	15.3	16.6	18.1	16.7	17.6	16.5	16.8	17.4	16.6	18.3	18.1	16.5	17.9	18.9	17.2

INDIVIDUAL DATA POINTS: CONTROL GROUP B - NORMAL SKULLS (Continued)

Skulls N-19, C.I. 123, C.I. 132, and Y-7 are paired with the adolescent occipitalized skulls; the other 12 are matched with the occipitalized adult skulls.

CrB(cm) = the greatest breadth of the cranium, measured by anthropometric calipers.

CrL(cm) = the greatest length in the mid-line of the cranium, measured by anthropometric calipers.

The values of Ba-ML(mm) and Ba-PNSOp(mm) are positive, when Ba is cephalad to the respective reference line.

The values of Ba-DGL(mm) and OC-DGL(mm) are positive, when Ba or OC is caudad to the reference line, DGL.

The values of pA-NPo(mm) and ANB are positive, when point A or the NA line is anterior to the lines NPo and NB respectively.

## CRITICAL VALUES OF "U" IN THE MANN-WHITNEY "U" TEST

$N_1, N_2$ P	11-11	11-12	12-12	15-15	15-16	16-16
0.05	34	38	42	72	77	83
0.025	30	33	37	64	70	75
0.01	25	28	31	56	61	66
0.001	15	17	20	40	43	48

Auble, D.: Extended Tables for the M-W Statistic (Tables 1,3,5,7). Bull. of the Institute of Ed. Research at Indiana University Vol. 1, no. 2, 1953.

## PROBABILITY OF "U" VALUES IN SMALL SAMPLE SIZE

$N_1, N_2 = 4 - 4$	"U"	P
	0	0.014
	1	0.029
	2	0.057
	3	0.100
	4	0.171
	5	0.243
	6	0.343
	7	0.448
	8	0.557

Mann, H.B. & Whitney, D.R.: Ann. Math. Statist. 18:52-4, 1947.

Siegel, Sidney: Nonparametric Statistics for the Behavior Sciences. New York, McGraw-Hill Book Company, 1956.

## CRITICAL VALUES FOR CORRELATION COEFFICIENTS

Correlation Coefficients <sup>1</sup>	Probability
$\pm 0.4973$	0.05
$\pm 0.6226$	0.01
$\pm 0.7420$	0.001

<sup>1</sup>Based on Degrees of Freedom (D.F.) = 14; sample size = 16.

Siegel, Sidney: Nonparametric Statistics for the Behavior Sciences. New York, McGraw-Hill Book Company, 1956.

## VITA

Gaylord Don Noren was born in Chicago, Illinois on October 21, 1942, the son of Dorothy T. Noren and Donald O. Noren. After graduating from Proviso East High School, Maywood, Illinois in 1960, he entered the University of Illinois, Urbana, Illinois and received the degree of Bachelor of Science in Liberal Arts and Sciences in 1964. Dr. Noren entered The University of Illinois, College of Dentistry and received the degrees of Bachelor of Science in Dentistry in 1966 and Doctor of Dental Surgery in 1968. Upon graduation, he was commissioned as a Captain in the United States Air Force and entered the Rotating Dental Internship program at Wilford Hall USAF Hospital, Lackland Air Force Base, Texas, successfully completed in 1969. Subsequently, he had assignments to Ching Chuan Kang Air Base, Republic of China (Taiwan), and the United States Air Force Academy, Colorado as a General Dental Officer. In July, 1973, Dr. Noren entered the three-year Oral Surgery Residency program at Wilford Hall USAF Medical Center, Lackland Air Force Base, Texas. In July, 1976, after successful completion of the Oral Surgery program, he entered the Postgraduate School of Dentistry at The University of Texas Health Science Center at Houston, Dental Branch, for one year of further study in Oral and Maxillofacial Surgery, sponsored by the Air Force Institute of Technology. Subsequently, he has been assigned to MacDill Air Force Base, Florida, and Chanute Air Force Base, Illinois, as Chief of Oral Surgery.

Dr. Noren is currently a Lieutenant Colonel in the United States Air Force. Since 1980 he has been Chief, Oral Surgery, at USAF Hospital Chanute, teaching oral surgery principles and techniques in a one-year Dental General

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THE EFFECTS OF OCCIPITALIZATION OF THE ATLAS ON FACIAL  
SKELETAL MORPHOLOGY(U) AIR FORCE INST OF TECH  
WRIGHT-PATTERSON AFB OH G D NOREN SEP 82

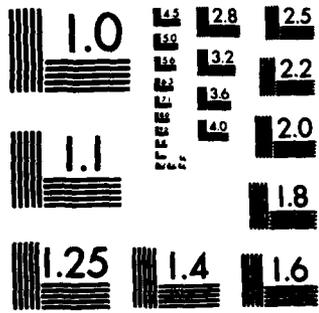
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Practice Residency. His military decorations include the Air Force Commendation Medal. He is a Diplomate of the American Board of Oral and Maxillofacial Surgery, conferred in 1979. His article, "Huge Osteoma of the Mandible: Report of Case," is published in the Journal of Oral Surgery, volume 36, number 5, May, 1978. He is a member of the American Dental Association, the American Association of Oral and Maxillofacial Surgeons, the Society of Air Force Clinical Surgeons, and the Air Force Association. Dr. Noren received the degree of Master of Science in September, 1982.

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This Thesis was typed by Betty J. Bouford.

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