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Mass, Volume, Center of Mass, and Mass Moment of Inertia of Head and Head and Neck of Human Body

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Abstract

The mass, volume, center of mass, and mass moment of inertia of the head and the head and neck were determined for 20 human male cadavers. Anthropometric values and anatomic landmarks were obtained by external measurements and by use of x-ray procedures. The procedures used to determine the above measurements are described. Uniform planes for the separation of the head and neck from the torso and separation of the head from the neck were established and are described in detail.

The values of the physical properties of the head and neck and the head are tabulated and compared to data reported in previous studies.

INVESTIGATIONS designed to predict the dynamic response of the human body during vertical (1-3)* and horizontal (4) accelerations have emphasized the need for reliable quantitative physical and anthropometric data on various segments of the human body. Previous studies of these parameters (5-11) were completed using small cadaver populations and/or substantial differences in experimental technique that have made it difficult to utilize some of the data reported. The present study was done to determine the location of the center of mass, the mass, volume, and the mass moment of inertia of the human head and neck as a unit, and of the human head as a unit. The data obtained have provided the physical constants necessary for more critical analysis of data accumulated during acceleration studies of human volunteers carried out by Ewing, et al. (4).

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*Numbers in parentheses designate References at end of paper.

Materials and Methods

The cadavers used in this study were selected from those available to the Department of Anatomy, Tulane University Medical Center. They had been embalmed by perfusion through the left femoral artery at a pressure of 15 psi. The embalming fluid was composed of propylene glycol 8.6%, phenol 6.7%, formaldehyde 2.5%, ethyl alcohol 34.4%, and water 47.8% by volume. Following embalming, the cadavers were stored supine on separate shelves at a temperature of 2°C ± 1°C. The density of the embalming fluid is 1.069, a density that closely approximates density of young men (1.063) and of blood (1.056) as reported previously (10). It was assumed that the volume of embalming fluid that remained in the cadavers was equal to the normal volume of body fluid, and that the mass distribution and density of the cadavers would approximate that of living individuals.

The criteria considered in selecting cadavers for the study were: they must be male, they must not be "wasted" by disease, they should be of normal weight and stature, and their ages at death should range from 20–50 years.

Following selection, the cadavers were subjected to a series of anthropometric measurements which, along with the methods used in measurement, are detailed in Appendix A. The values determined by these measurements are presented in Tables A-1 and A-2. Upon completion of the measurements, the bony landmarks used during separation of the head and neck from the torso and separation of the head from the neck were located by palpation. The position of the landmarks was verified by placing lead markers on the body surface and taking x-rays of the head and neck with the Frankfort plane horizontal to the floor.

The plane along which the head and neck was separated from the torso extends from the superior surface of the medial end of the clavicles anteriorly through the intervertebral disc between the seventh cervical and first thoracic vertebrae posteriorly. In each instance, attempts were made to divide the soft tissue of the neck on the same supero-inferior plane. However, a slight elevation of the shoulders occurred during embalming and storage which dictated that the most lateral point of the plane should lie at a slightly more superior level. The plane established for separation of the head and neck from the torso is shown in Fig. 1. The mass, volume, mass moment of inertia, and the location of the center of mass were then determined for the head and neck.

The head was separated from the neck along a plane that originates at a point 3/4 in below the external occipital protuberance, and continues anteriorly and inferiorly through the atlanto-occipital joint to a point anterior to the prevertebral muscle mass. At this point, it intersects with a plane that originates at a point immediately inferior to the hyoid bone and extends superiorly and posteriorly to the intersection described above. The plane established for separation of the head from the neck is shown in Fig. 2. The mass, volume, mass moment of inertia, and the location of the center of mass were then determined for the head.

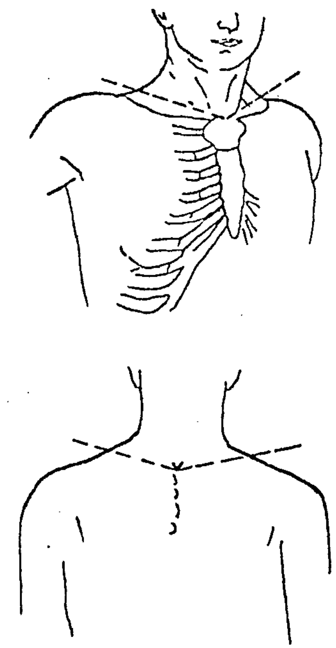

Fig. 1—Plane of separation of head and neck from torso

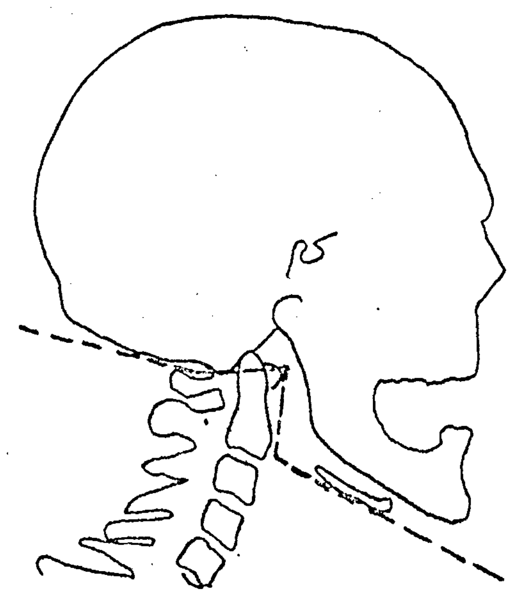

Fig. 2—Plane of separation of head from neck indicated on tracing of lateral radiograph

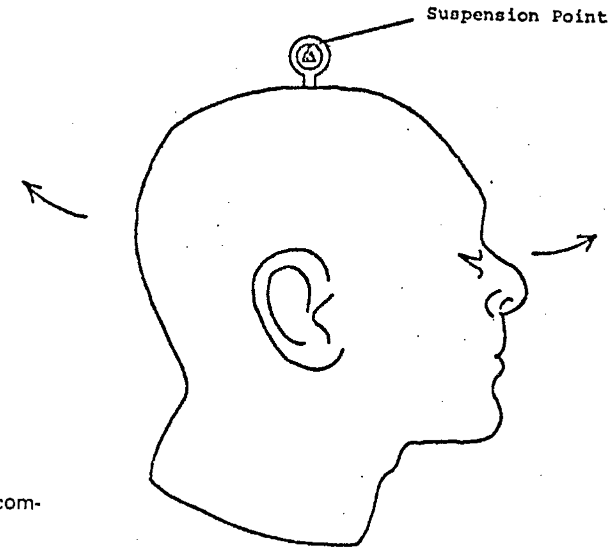

Fig. 3—Head being swung as compound pendulum

Table 1—Data on Cadavers

Test No.	Cadaver No.	Age at Death	Cause of Death
1	3029	46	Suffocation
2	2986	41	Pulmonary abscess
3	3121	51	Stroke
4	3079	70	Emphysema
5	3142	69	Unknown
6	3072	58	Emphysema
7	3055	67	Heart disease
8	3107	56	Pneumonia
9	3106	45	G. I. hemorrhage
10	3061	59	Emphysema
11	3129	64	Respiratory failure
12	3111	63	Respiratory failure
13	3114	61	Pneumonia
14	3117	74	Heart disease
15	3026	74	Myocardial infarction
16	3152	70	Cardiac arrest
17	3125	63	Chronic lung disease
18	3356	79	Unknown
19	3343	68	Stroke
20	3328	61	Cardiac arrest

When each head and neck unit and each head unit had been appropriately separated, the determinations we required were made, as indicated below, not necessarily in the order presented.

The unit mass was determined by computation subsequent to weighing the unit on a Fairbanks Morse scale.

The volumes were determined by water displacement using a plexiglass cylinder with a calibrated hook gage. The volume of the unit was computed as the difference between the volume of water added to the empty cylinder and the volume of water added to the cylinder with the unit contained within it. On repeated measurements, our results were reproducible to within ± 15 cm^3.

To determine the center of mass with respect to external surface features, two small screw-eyes were inserted along the midsagittal plane widely separated from each other. The unit was suspended in a wood frame with a plumbline behind the unit for sighting purposes. Photographs of the right lateral surface were made while the unit was suspended from each of the screw-eyes, and the location of the center of mass was determined as the intersection point of vertical lines passing through each suspension point. A 10 cm scale at the midsagittal plane was included in each photograph. To locate the center of mass radiographically, a small skin incision was made at the superior margin of each external auditory meatus and at the lowest point on the inferior rim of each orbit. A lead shot was inserted through each incision and positioned on bone at these locations. The unit was hung from the same two suspension points, and right lateral radiographs were made. The suspension material was soft, radiopaque wire, and the intersection of vertical lines (delineated by the radiopaque wire) through each of the suspension points indicated the location of the center of mass. A 10 cm scale in the midsagittal plane was included in each radiograph.

A hole was drilled through the calvaria in the midsagittal plane and a screw eyebolt was attached, so that a line extending the axis of the screw passed through the center of mass. The unit was swung as a compound pendulum, as shown in Fig. 3. The mass moment of inertia about the y-axis (a line connecting the midpoint of each external auditory meatus) I_{yy} was then calculated

$$I_{yy} = I_{yy}' - I_{yy}'' - m(d)^2 \tag{1}$$

where:

I_{yy} = mass moment of inertia of unit under study about its centroidal axis
I_{yy}' = mass moment of inertia of compound pendulum, in total
I_{yy}'' = mass moment of inertia of eyebolt about suspension point
$m(d)^2$ = correction term from swing axis to centroidal axis

The mass moment of inertia was computed for the pendulum using

$$I = \frac{mgdt^2}{(2\pi)^2} \quad (2)$$

where:

m = mass of pendulum
g = acceleration of gravity (980.665 cm/s²)
d = distance from centroidal axis to swing axis
t = period for one swing of pendulum

Table 2—Values for Mass, Volume, and Specific Gravity of Head and Neck Unit and Head Unit

Test No.	H + NM	H + NV	H + NSG	HM	HV	HSG
1	3688.	3670.	1.005	2835.	2830.	1.002
2	6215.	5760.	1.079	4703.	4540.	1.036
3	5275.	5350.	0.986	4104.	4100.	1.001
4	5911.	5475.	1.080	4184.	4120.	1.016
5	6896.	5710.	1.205	*	*	*
6	5770.	5165.	1.117	4275.	3900.	1.096
7	5398.	4820.	1.120	3930.	3860.	1.018
8	7673.	6110.	1.256	5755.	4550.	1.265
9	6533.	5655.	1.155	5128.	4260.	1.204
10	6883.	6335.	1.087	5069.	4450.	1.139
11	6361.	5605.	1.135	4375.	3760.	1.164
12	5907.	4900.	1.206	4288.	3700.	1.159
13	5798.	5265.	1.101	4273.	4150.	1.030
14	5693.	4950.	1.150	4139.	3690.	1.122
15	5758.	4485.	1.284	4186.	3510.	1.193
16	5985.	4405.	1.359	4459.	3500	1.274
17	5493.	5145.	1.068	4153.	3940.	1.054
18	6436.	5824.	1.105	4531.	4086.	1.109
19	6192.	5977.	1.036	4377.	4102.	1.067
20	6164.	6421.	0.960	*	*	*
MN	6001.	5351.	1.125	4376.	3947.	1.108
SD	±790.	±687.	±0.100	±591.	±421.	±0.088

H + NM—Head and neck mass, g
H + NV—Head and neck volume, ml
H – NSG—Head and neck specific gravity
HM—Head mass, g
HV—Head volume, ml
HSG—Head specific gravity
MN—Mean
SD—Standard deviation

*Value not determined.

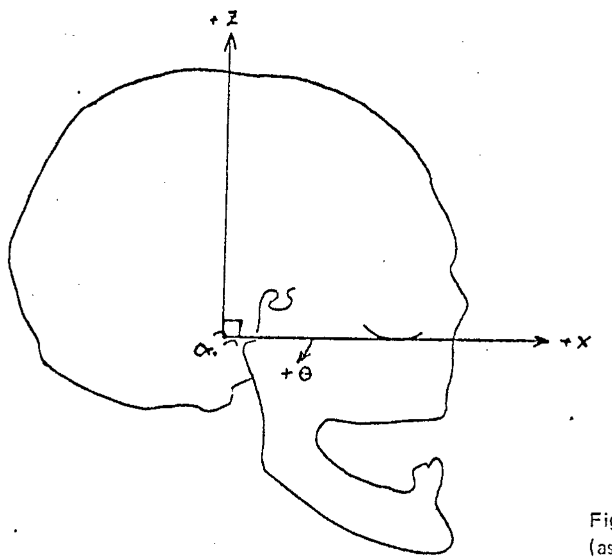

Fig. 4—Head coordinate system (as described by Ref. 12)

Table 3—Center of Mass Locations for Head and Neck

Test No.	X-Ray R, cm	X-Ray θ, deg	Photo R, cm	Photo θ, deg
1	*	*	*	*
2	*	*	0.9	317.7
3	*	*	1.1	301.4
4	*	*	0.5	142.5
5	0.9	166.8	1.8	164.9
6	0.2	303.9	1.9	275.3
7	0.4	142.0	2.2	295.0
8	1.1	231.2	0.7	158.5
9	*	*	0.7	42.5
10	1.5	112.9	0.8	64.1
11	1.6	96.4	*	*
12	0.7	125.0	0.9	227.4
13	0.2	219.1	1.3	331.0
14	0.3	130.5	0.8	155.0
15	1.4	178.8	0.8	164.0
16	0.2	180.0	0.6	264.7
17	1.2	79.0	0.3	76.8
18	1.6	159.5	1.8	203.5
19	0.6	*	1.2	106.0
20	0.7	216.5	1.8	90.0

*Value not available.

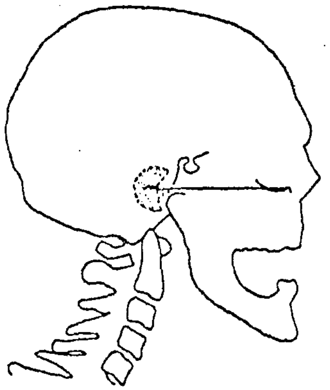

Fig. 5A—Lateral x-ray of head and neck

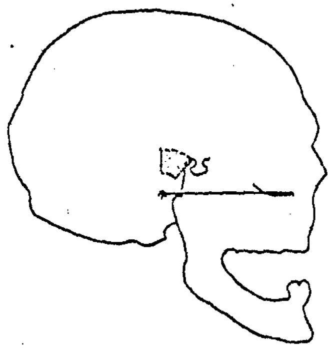

Fig. 5C—Lateral x-ray of head

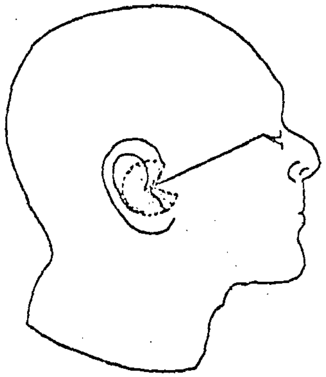

Fig. 5B—Lateral surface projection of head and neck

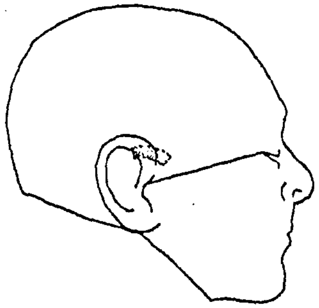

Fig. 5D—Lateral surface projection of head

Fig. 5—Ranges for location of center of mass

Results

Most of the results of the study can best be presented in tabular form.

All criteria but that of age were satisfied in the selection of the cadavers studied. The average age for the group was 62 years with a range from 41–79 years. The ages and causes of death of the cadavers are presented in Table 1. Values for mass, volume, and specific gravity are shown in Table 2.

Table 4—Center of Mass Locations for Head

	X-Ray		Photo	
Test No.	R, cm	θ, deg	R, cm	θ, deg
1	*	*	*	*
2	2.0	309.5	2.7	324.1
3	2.5	313.4	3.2	313.6
4	2.0	277.6	2.2	309.0
5	*	*	*	*
6	2.6	284.2	3.6	287.5
7	2.0	269.0	2.2	302.2
8	2.0	301.0	2.8	306.5
9	2.2	313.5	3.2	316.5
10	1.3	299.9	1.9	330.5
11	2.7	293.1	3.5	307.0
12	2.9	284.5	3.2	293.4
13	3.0	286.9	1.5	270.0
14	2.4	288.5	1.7	279.0
15	2.6	273.1	2.7	286.4
16	2.5	291.9	5.3	267.0
17	2.2	308.0	2.4	321.5
18	2.6	260.1	4.2	289.0
19	3.6	315.5	3.5	315.5
20	*	*	*	*

*Value not available.

Table 5—Mass Moment of Inertia Values About Y-Axis, g-cm²

Test No.	Head and Neck	Head
1	*	*
2	*	254000.
3	*	236000.
4	447000.	211000.
5	533000.	*
6	425000.	217000.
7	403000.	157000.
8	567000.	323000.
9	423000.	293000.
10	496000.	238000.
11	498000.	234000.
12	463000.	228000.
13	442000.	216000.
14	434000.	198000.
15	411000.	218000.
16	365000.	239000.
17	388000.	215000.
18	357000.	258000.
19	425000.	230000.
20	508000.	*

*Value not determined.

Table 6—Comparison of Selected Mean Values

	Ref. 13	Ref. 7	Ref. 10
Sample Size	20	8	13
Age	62	69	49.31
Weight, kg	66.4	57.99	66.52
Stature, cm	174.8	169.4	172.72
H + N mass, g	6001	4610	4749*
H + N volume, ml	5351	4150	4418*
H + N specific gravity	1.13	1.11	1.07
Head mass, g	4376	4610*	4729
Head volume, ml	3947	4150*	4418
Head specific gravity	1.11	1.11*	1.07
H + N I_{yy}, g-cm²	4.46 × 10^5	(1.42 × 10^6)**	†
Head I_{yy}, g-cm²	2.33 × 10^5	†	†

*Calculated from data given in these reports.
**Referenced to C7.
†Value not available because of differences in technique.

Although the skeletal structure of the human head is fairly uniform, the degree of variation in position of easily recognizable landmarks prompted us to search for a system for describing the location of the center of mass which offered a greater degree of reliability than could be expected by referencing to a single skeletal landmark. The system chosen is that described by Thomas and Ewing (12). This coordinate system has its origin at the midpoint of a line between the external auditory meatuses. It is assumed that this point is in the mid-sagittal plane. The x-axis is positive anteriorly and passes through a plane horizontal to the most inferior point of the right inferior orbital margin. The z-axis lies in the mid-sagittal plane, 90 deg from the x-axis, and is positive superiorly. The y-axis is a line between the midpoint of each external auditory meatus, is positive toward the left meatus, and is perpendicular to the midsagittal plane. This coordinate system is shown in Fig. 4. Since it was not possible to identify the origin of the coordinate system in the photographs of the lateral surface of each unit, a modified x-axis for reference to surface topography was described. The modified x-axis has its origin at the most superior-posterior point of the tragus and extends anterosuperiorly to the lateral canthus of the palpebral fissure. Using these coordinate systems, the location of the previously plotted center of mass on each x-ray and photograph was measured relative to the origin of the x-axis as follows. The distance R from the origin of the x-axis to the center of mass was measured with calipers and recorded in cm. The angle θ from the origin of the x-axis to the center of mass was measured in a clockwise direction with a protractor and recorded in degrees. Reproducibility for angular measurements was 0.5 deg and for the distance measurements was 1.0 mm. The ranges plotted for the center of mass are shown in Fig. 5, and the measurements are given in Tables 3 and 4. The mass moments of inertia calculated are listed in Table 5, and Table 6 presents selected mean values from the present study compared with values obtained in the studies of Dempster (7) and Clauser (10).

Summary and Conclusions

The values of mass, volume, center of mass, and mass moment of inertia for the head and for the head and neck were determined. A comparison of these results with previous studies (7, 9, 10) shows no marked differences between the values. In the present study, however, a procedure for accurate location of the center of mass has been used. The planes that have been established for separation of the head and neck units from the torso and the head units from the neck will hopefully provide a more functional rationale for future studies. The data presented are presently being used in the program for which they were requested, and plans are being made for the study of a larger population sample.

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Appendix A

Descriptions of Anthropometric Measurements and Methods

Definitions are listed below, and anthropometric values are shown in Tables A-1 and A-2.

1. Age and cause of death: as recorded in Anatomical Board files.
2. Weight: by mass measuring device provided by Naval Aerospace Research Institute, and scales reading to the nearest 0.25 lb and nearest 0.1 g as applicable.
3. Standing height: cadaver supine with the head oriented with Frankfort plane perpendicular to floor. Using large sliding caliper, measure distance from top of head to the most distal portion of the right heel.
4. Sitting height: cadaver supine as above with right leg flexed to form 90 deg angle to torso. Using large sliding caliper, measure distance from surface of skin superficial to the ischial tuberosity to top of head.
5. Head length: using spreading calipers, measure the maximum length of the head between the glabella and the maximal occipital point.
6. Head breadth: using spreading calipers, measure the maximum horizontal breadth of the head.
7. Bregma to gnathion: using spreading calipers, measure the length between the bregma and gnathion.
8. Bizygomatic diameter: using spreading calipers, measure the greatest distance between most lateral points of zygomatic bone.
9. Height of head: using sliding calipers, measure the distance between the external auditory meatus to the top of the head, in a plane perpendicular to the Frankfort plane.
10. Total facial length: using sliding calipers, measure the length between nasion and the gnathion.
11. Lateral orbital width: using spreading calipers, measure the length between the most lateral points of the orbit rims.
12. Circumference at larynx: using a meter tape, measure the circumference at the larynx with the head in the Frankfort plane.
13. T-1 to external occipital protuberance: using spreading calipers, measure the distance between the anterior superior margin of the body of T-1 and the external occipital protuberance from an x-ray taken while the head was in the Frankfort plane.
14. Transverse diameter of neck: using spreading calipers, measure the transverse diameter of the neck at the level of thyroid cartilage.
15. Anterior-posterior diameter of the neck: using spreading calipers, measure the anterior-posterior diameter of the neck at the level of the thyroid cartilage.

Table A-1—Anthropometric Values

TN	TBW	TORSOW	BLS	SH	HL	HB	BG
1	43940.0	40310.0	167.5	*	18.2	15.5	21.5
2	66680.0	60470.0	180.9	94.5	19.0	17.0	*
3	68210.0	62940.0	179.2	91.9	25.2	18.6	*
4	69460.0	63550.0	173.7	89.8	19.3	15.7	23.0
5	71390.0	64500.0	183.0	94.5	19.6	15.1	21.0
6	60240.0	54880.0	174.8	91.5	20.3	16.4	22.8
7	45900.0	40360.0	165.2	90.7	18.2	15.6	21.0
8	90350.0	83170.0	176.5	94.9	19.1	17.2	21.5
9	78230.0	71600.0	173.4	94.2	19.5	15.1	18.3
10	86170.0	78770.0	180.7	96.5	21.0	15.4	20.7
11	72910.0	66650.0	182.0	97.3	18.9	16.2	22.1
12	54620.0	48490.0	177.6	95.2	20.1	14.5	22.1
13	58160.0	50670.0	171.3	91.5	20.3	16.3	21.5
14	64920.0	58570.0	177.5	94.0	19.1	14.7	22.1
15	65920.0	60160.0	185.7	96.5	20.6	15.5	22.5
16	55210.0	49120.0	167.7	87.3	19.3	16.7	22.2
17	54340.0	48850.0	170.0	89.3	19.3	15.0	21.5
18	73350.0	66950.0	180.5	97.5	19.7	14.4	23.3
19	77430.0	70970.0	171.3	88.1	18.6	14.4	20.2
20	70490.0	64310.0	157.1	78.8	20.4	13.7	21.6
MN	66401.0	60265.0	174.8	92.3	19.8	15.6	21.6
SD	±12173.0	±11606.0	±7.0	±4.5	±1.5	±1.2	±1.2

TN—Test number
TBW—Total body weight, g
TORSOW—Torso weight, g
BLS—Body length supine, cm
SH—Sitting height, cm
HL—Head length, cm
HB—Head breadth, cm
BG—Bregma to gnathion, cm
MN—Mean
SD—Standard deviation

*Value not available.

Table A-2—Anthropometric Values, cm

TN	BZD	HH	TFL	LOW	CL	T1EOP	TDON	APDN
1	13.9	13.2	11.9	10.1	37.5	13.7	11.6	12.6
2	15.5	12.8	13.4	11.1	45.8	19.6	16.1	11.9
3	14.0	12.2	13.9	11.0	42.5	17.8	12.8	12.5
4	13.5	12.5	12.8	11.8	39.5	15.6	12.7	11.0
5	12.8	12.3	12.3	10.2	38.5	13.6	10.8	13.1
6	13.7	13.8	11.2	11.3	42.5	11.6	12.1	16.2
7	13.6	13.2	12.5	9.1	38.7	13.3	13.6	12.2
8	15.2	13.6	13.1	12.4	42.1	12.5	15.6	13.3
9	14.5	13.9	14.6	12.1	39.4	12.8	11.4	11.0
10	13.1	12.5	12.2	9.0	49.8	10.0	15.0	13.6
11	13.3	13.3	13.5	9.9	42.5	11.9	11.4	12.7
12	11.7	12.5	11.5	10.1	40.0	11.1	11.6	12.6
13	11.3	12.9	10.7	11.7	40.5	13.8	10.8	12.1
14	11.8	11.8	11.8	8.9	41.0	14.4	12.3	12.8
15	12.3	12.9	12.4	9.4	38.0	14.0	11.1	11.6
16	11.9	12.4	12.1	9.4	44.0	12.1	14.4	12.4
17	12.1	12.5	12.4	9.6	40.5	13.1	11.5	12.0
18	12.5	13.1	13.7	9.3	*	14.5	10.5	12.6
19	12.4	13.2	12.6	9.9	*	12.3	10.6	12.7
20	13.4	13.9	12.5	9.3	*	11.0	*	*
MN	13.1	12.9	12.6	10.3	41.3	13.4	12.4	12.6
SD	±2.1	±0.6	±0.9	±1.1	±3.1	±2.3	±1.7	±1.1

TN—Test number
BZD—Bizygomatic diameter
HH—Height of head
TFL—Total facial length
LOW—Lateral orbital width
CL—Circumference at larynx
T1EOP—T1 to external occipital protuberance
TDON—Transverse diameter of neck
APDN—Anterior posterior diameter of neck
MN—Mean
SD—Standard deviation

*Value not available.