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**SUBGLOTTAL PRESSURE AND AIR FLOW MEASURES
DURING VOCAL FRY PHONATION**

by

Thomas Murry

Bureau of Medicine and Surgery, Navy Department

Research Work Unit MF12.524.004-9011D.04

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PHYSICS DEPARTMENT

5300 S. DICKINSON DRIVE

CHICAGO, ILLINOIS 60637

TEL: 773-936-3700

FAX: 773-936-3700

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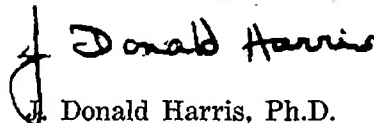
SUBGLOTTAL PRESSURE AND AIR FLOW MEASURES
DURING VOCAL FRY PHONATION

by
Thomas Murry

SUBMARINE MEDICAL RESEARCH LABORATORY
U. S. NAVAL SUBMARINE MEDICAL CENTER REPORT NO. 611

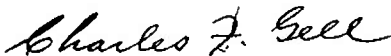
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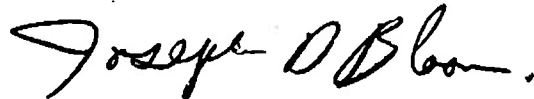
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Head, Auditory Research Branch

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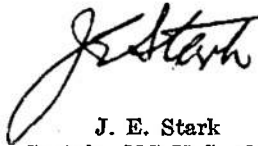
Charles F. Gell, M.D., D.Sc. (Med)
Scientific Director, SubMedResLab

Reviewed and Approved by:



J. D. Bloom, CDR MC USN
Director, SubMedResLab

Approved and Released by:



J. E. Stark
Captain, MC U. S. Navy
COMMANDING OFFICER, SUBMEDCEN

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SUMMARY PAGE

THE PROBLEM

To determine the subglottal air pressures and mean air flow rates which accompany vocal fry phonation.*

FINDINGS

Subglottal pressures were found to be higher during vocal fry phonation than during low frequency modal phonation. Furthermore, the vocal fry phonatory frequency increased as the subglottal pressure increased. Mean air flow rates were found to be lower in vocal fry than in modal range phonation and were not related to the fundamental frequency of phonation.

APPLICATION

The information in this report provides theoretical implications concerning the operation of the vocal folds during a type of phonation (vocal fry) which is typically found at the onset and termination of most speech utterances. An understanding of the operation of the vocal folds during this type of phonation appears necessary in the general development of a theory of normal laryngeal behavior. This has applicability to the development of improved underwater communication systems required by Navy divers.

* The urrrr . . . type of vocal pause often heard at the beginning or end of groups of words.

ADMINISTRATIVE INFORMATION

This investigation was conducted in part under NIH Grants NB-05475 and MB-06459. A fuller version under the same title was submitted in partial fulfillment of the requirements of the Ph.D. to the University of Florida. The present report is No. 4 on Work Unit MF12.524.004-9011D,—Procedures for Improving Underwater Verbal Communication Capabilities in Submarine and Deep Submergence Operations." It was approved for publication as of 30 January 1970, and designated as Submarine Medical Research Laboratory Report No. 611.

PUBLISHED BY THE NAVAL SUBMARINE MEDICAL CENTER

SUBGLOTTAL PRESSURE AND AIR FLOW MEASURES DURING VOCAL FRY PHONATION*

I. INTRODUCTION

Within a theoretical framework advanced by Hollien, et al¹, vocal fry phonation has been shown to have attributes characteristic of normal phonation. That is, vocal fry can be produced in a series of consecutive fundamental frequencies having a similar quality. The current interest in vocal fry phonation has resulted in a number of investigations dealing primarily with the acoustic attributes of fry as summarized by Hollien and Wendahl² and by Hollien, Damste and Murry³. Specifically, previous investigations of vocal fry have shown that men and women can produce vocal fry pulse rates which range from approximately 15-80 pulses per second (Hollien and Michel⁴). It has also been shown that the acoustic signal accompanying vocal fry production consists of a pulse-like waveform which is damped almost to zero prior to the onset of the next cycle (Wendahl, Moore and Hollien⁵). Coleman⁶ has shown the importance of this damped waveform in the perception of vocal fry. He found that with sufficient damping 42-44 dB of the maximum amplitude), subjects always perceived the signal as vocal fry; with only 30 dB of damping, vocal fry was never perceived. In addition to the acoustic analyses of vocal fry phonation, some attempts have also been made to describe the physiological operation of the vocal folds during vocal fry within the framework of the myoelastic-aerodynamic theory of voice production (Van den Berg,⁷). In an investigation of glottal waveforms, Timke, Von Leden, and Moore⁸, using high speed motion picture photography, found

that the vocal fry glottal waveform was a result of a pulse-like opening and closing of the folds followed by a long closed phase. This finding would tend to support Coleman's⁶ results.

Several studies have also been done to determine if the physiological mechanisms used to produce variations in the modal register also produce variations in vocal fry. Investigations of the larynx during modal phonation have shown the fundamental frequency to be highly correlated with vocal fold length¹, mass and thickness² and the subglottal pressures (Kunze²²) needed to maintain vocal fold movement. While considerable data have been presented showing the relationship between fold length and fundamental frequency of phonation in the modal range, the length of the folds was not found to vary as a function of the fundamental frequency in vocal fry (Hollien, Damste, and Murry³).

Investigations of vocal fold thickness have generally shown that, as the fundamental frequency of phonation decreases, the thickness of the vocal folds increases. The thickness of the folds during fry has not been observed systematically; however, several investigators (Hollien²³, Hollien, Damste, and Murry³) have noticed the folds to be relatively thick during vocal fry.

Investigations of laryngeal aerodynamics have shown certain relationships within the modal phonational range, but little is known about these relationships in vocal fry. For example, Kunze^{22, 24}, Isshiki²⁵, and Perkins and Yanagihara²⁶ investigated mean rate of air flow over a wide range of fundamental

*Vocal fry is a type of phonation characterized by a distinct popping or pulsing sound of low frequency. It is a vocal register at the low end of the frequency continuum, just as falsetto is at the high end of the pitch range. It is often used at the beginning or end of phonation,—a vocal pause, so-to-speak, consisting of an r-r-r often heard at the beginning and ending of word groups.

¹ Irwin⁹, Brackett¹⁰, Sonninen^{11, 12}, Hollien¹³, Hollien and Moore¹⁴, Hollien¹⁵, Wendler¹⁶, Damste, Hollien, Moore and Murry¹⁷.

² Hollien and Curtis¹⁸, Hollien^{19, 20}, Hollien, Coleman and Moore²¹.

frequencies and found a positive relationship between air flow rate and intensity. These investigators found air flow rate to have little or no relation to the fundamental frequency of phonation.

Air flow rates during sustained vocal fry phonation have been obtained by McGlone²⁷ using a wet spirometer. He found flow rates ranging from 2.0 ml/sec to 71.9 ml/sec for repetition rates ranging from 10.9 to 52.1 pps. No systematic relationship between flow rate and fundamental frequency during vocal fry was found.

As yet, there are no data concerning the results of the subglottal pressures generated during vocal fry phonation. Several investigators, however, have obtained subglottal pressure measures for low frequency modal phonation of the vowel /a/ (Van den Berg²⁸, Isshiki²⁹, Ladefoged³⁰, Kunze²², Lieberman³¹) which appear to conflict somewhat. Van den Berg²⁸ reported a mean subglottal pressure of 10 cm H₂O for phonation at 145 Hz as compared to 9 cm H₂O for phonation at 97 Hz. Isshiki²⁹ found an average subglottal pressure of 9 cm H₂O for sustained phonation at 123 Hz and 5.5 cm H₂O for phonation at 98 Hz. While Ladefoged's³⁰ results show a similar trend, Kunze²² noted that as the subject produced tones below or above the 30 percent point of his phonational range, subglottal pressure increased. (It may be some importance to note that Kunze measured subglottal pressure directly in the trachea while the other investigators used an esophageal

balloon to obtain indirect records of subglottal pressure.) Thus, it appears that increases in the subglottal pressure are accompanied by increases in the fundamental frequency of phonation, at least over the upper part of the phonational range. Due to the sampling techniques and the direct vs indirect recording procedures as discussed by Kunze²⁴ and Lieberman³¹, the relationship between the fundamental frequency of phonation and subglottal pressure is not clear especially at the low frequency end of the modal phonational range.

In order to understand the aerodynamic operation of the laryngeal mechanism during vocal fry, it would appear necessary to obtain quantitative information on both the subglottal air pressures and air flow rates as they relate to changes in repetition rate of vocal fry phonation. The major purpose of this study, therefore, was to determine the subglottal pressures and rates of air flow produced during vocal fry and low frequency modal phonation. A second purpose was to investigate the relationship between the fundamental frequency of phonation in vocal fry and both subglottal air pressure and rate of air flow.

II. PROCEDURE

A diagram of the instrumentation employed in the present study is shown in Figure 1. While the subject phonated in a supine position, the subglottal pressure was measured directly through a hypodermic needle between the first and second tracheal rings;

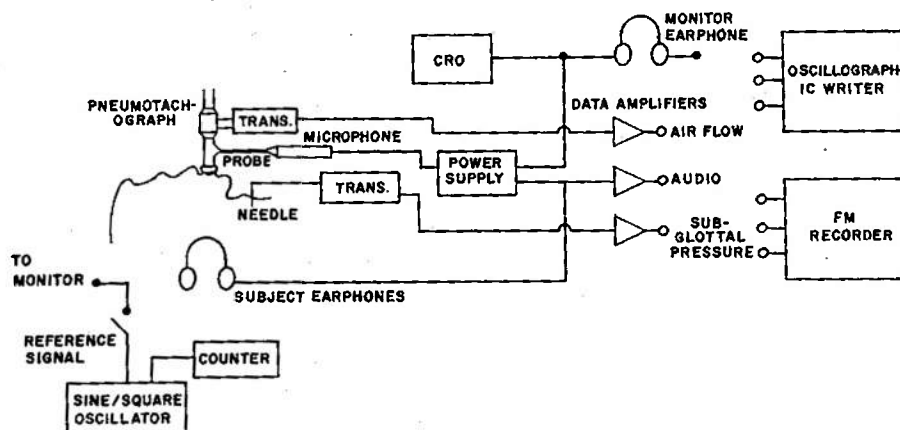


Fig. 1. Block diagram of equipment used to provide the reference signals, record the subglottal air pressure, air flow and voice signals, and monitor subject's output.

air flow was measured through a pneumotachograph connected to a mouthpiece and held in place by a flange fitting between the lips and teeth. Mouth pressure was measured with a microphone and probe tube inserted in the connecting tube of the pneumotachograph. Following amplification by separate channels of a data amplifier each of the three signals was recorded simultaneously on an oscillographic writer and an FM magnetic tape recorder. In order to monitor the phonatory samples produced by the subjects, an acoustic wave was displayed on the face of an oscilloscope in view of the subject and experimenter and also was presented to each of them by means of individual earphones. In addition, the subject was fitted with a second earphone to monitor the reference signals generated by a sine-wave generator for modal phonation and a square-wave generator for vocal fry.

Instrumentation for Measuring and Calibrating Subglottal Pressure.

Subglottal pressure was measured using an 18 gauge hypodermic needle (3.5 inches long with an inside diameter of .033 inches) inserted between the first and second tracheal rings so that it was perpendicular to the flow of air through the trachea. The other end of the needle was connected to the Statham PM 131 TC differential transducer via a 12 cm plastic tube having an inside diameter of .125 inches. The resultant electrical signal was amplified by an Electronics-for-Medicine DR-8 dc pressure amplifier and recorded simultaneously on one channel of an associated Multitrace Oscillographic Writer and on one channel of a Honeywell 8100 FM Magnetic Tape Recorder. The intratracheal pressure measuring system was calibrated daily by reference to a U-tube manometer scaled in centimeters of water (cm H₂O).

Instrument for Measuring Air Flow.

Air flow was measured by a Fleish Number 0 pneumotachograph. The pneumotachograph was connected to a mouthpiece 2.12 inches in length and held in place by a flange fitting between the lips and the teeth. This device, used with a nose clip appeared to provide reliable measures of air flow while avoiding the problems of dead air spaces and improperly

fitting face masks experienced by previous investigators (Isshiki²⁰, Kunze²²). The pneumotachograph was then connected through a Statham PM97 pressure transducer to the amplifier and recording systems.

Calibration of the air flow recording system was accomplished by passing a known flow rate produced by a variable speed vacuum cleaner through a rotameter and to the transducer.

Subjects.

Five adult males were selected for the investigation on the basis of the following criteria: 1) they were capable of phonating in vocal fry over a range of repetition rates; 2) they showed no evidence or history of voice disorders or laryngeal pathology; and 3) they were willing to perform the task.

Prior to the experimental task, each subject's modal and vocal fry phonational ranges were determined. The modal range was determined in the traditional fashion by having the subject match a recording of the musical scale until he produced his highest and then his lowest sustainable notes.

The vocal fry range was determined by a procedure similar to that described by Hollien and Michel⁴. Specifically, each subject practiced producing vocal fry at various repetition rates, then varied the rates upward and downward until reaching the lowest and highest sustainable repetition rate. When the experimenter and subject agreed upon these limits, a 4-second sample was recorded on magnetic tape. To obtain fundamental frequency, tape loops of the samples were analyzed through a General Radio 1900-A Wave Analyzer set to a three-cycle bandwidth coupled to a Hewlett-Packard 5214L Preset Counter.

The modal and vocal fry phonational ranges for five subjects are shown in Table I.* In Table I it can be seen that certain values in the vocal fry phonational ranges are higher than those reported in the previous study of phonational ranges (Hollien and Michel⁴). During the experimental sessions, only Subjects 3 and 4 produced fundamental frequencies which exceeded previously obtained

*See page 8.

vocal fry range limits. These relatively high frequency vocal fry samples obtained during experimental sessions were accepted for analysis on two bases: 1) the subject and experimenter agreed that the subject was producing vocal fry, and 2) the subglottal pressures and air flows associated with these samples were similar to those produced by the subjects at lower vocal fry frequencies and dissimilar to pressures and flow rates found for low frequency modal range phonation.

Tasks.

After administering a local anesthetic (one percent xylocaine) to the laryngeal area, a physician inserted the hypodermic needle. The needle was connected to the transducer and the subject was given ample time to adjust to the experimental apparatus. In the first series of recordings, each subject was instructed to produce three samples of the vowel /a/ and /i/ at relatively slow, medium, and fast repetition rates of his vocal fry phonational range as well as at his 10 and 30 percent points of the modal range. Subsequently, the mouthpiece leading from the pneumotachograph was fitted while the needle was still in place and the subject was asked to produce samples of the /a/ at the three vocal fry and two modal range frequencies. Thus, in the first series of recordings subglottal pressure was recorded during phonation of the two vowels at five frequencies; in the second series subglottal pressure and air flow were recorded for only the vowel /a/ at the five frequency conditions. The phonemic quality of /i/ appeared to be greatly distorted and was, therefore, not recorded while the mouthpiece was in place. The means of three three-second samples at a particular phonation condition were computed from measurements every 100 msec for pressure, and air flow rate and used as the criterion measures. The fundamental frequency data were analyzed from the Honeywell FM tape recorder. The tape recorder was slowed by a factor of 8 and played through a Sanborn 150-1330 D dynograph; wave-to-wave measures of the output were made.

III. RESULTS

Subglottal Pressure During Phonation.

The mean subglottal pressures for the vowels /a/ and /i/ produced at three vocal fry and two modal frequency regions of the subject's ranges are shown in Figure 2. The mean subglottal pressures for the combined group of subjects phonating /a/ at the five regions were 8.18, 8.55, 9.66, 6.84, and 5.32 cm H₂O; for the /i/, the mean values were 8.92, 9.08, 10.73, 6.82, and 6.20 cm H₂O. Figure 2 clearly indicates that the subjects subglottal air pressure was greater in vocal fry than in the two modal range conditions and that as subjects increased subglottal pressure, the frequency of phonation increased. Moreover, there were no reversals in this trend at any phonation condition. It can also be seen that as subjects increased subglottal pressure in vocal fry, the frequency of phonation increased similarly for both vowels, /a/ and /i/. In Figure 3, the mean subglottal pressure is plotted as a function of the frequency of phonation in vocal fry. The data points in this figure represent the mean pressure for each of three samples at each of the three phonation conditions for the vowel /a/ in fry. Figure 3 indicates the same general trends as shown for the grouped data in Figure 2 and in addition, demonstrates considerable variability (intersubject) in subglottal pressure across the samples.

In view of the variability³ for the modal range conditions exhibited by the subjects, it can only be shown that subglottal pressures decreased as the fundamental frequency approached the 30 percent region of a subject's modal phonational range.

To determine if the changes in subglottal pressure as a function of the five phonation conditions (i.e., slow, medium, and fast fry, and 10 and 30 percent modal), and vowels were statistically significant, a treatments by treatments by subjects analysis of variance was performed. The resulting F ratio for

³ While all subjects did not produce all samples at the exact 10 and 30 percent frequencies of their modal phonational range, the means of the three samples were within three semitones of the desired frequency.

phonation conditions was 4.52 ($F_{.05, 4, 16} = 3.01$); the effects due to vowels and the AB interaction were not statistically significant at the tested level. The Newman-Keuls test was applied to the data to determine which phonation conditions accounted for the overall significance. The results of this test indicated that with the exception of the slow-medium fry comparison, the subglottal pressures in all phonation conditions were significantly different from each other.

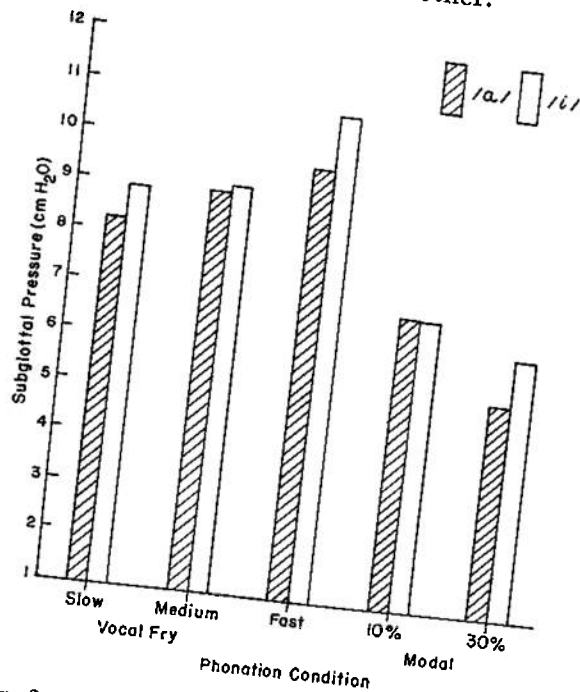


Fig. 2. Subglottal pressure (cm H₂O) plotted for the vowels /a/ and /i/ during three vocal fry and two modal phonation conditions.

As described previously, subglottal pressures for the vowel /a/ were recorded when the subject had a mouthpiece inserted for the purpose of measuring air flow rate and when the mouthpiece was not inserted. Figure 4 presents the results of the mean subglottal pressures for the /a/ under these two conditions as a function of phonation condition. The mean pressures without the mouthpiece for the five subjects were 7.84, 7.36, 8.62, 5.63, and 4.46 cm H₂O for the vowel /a/.

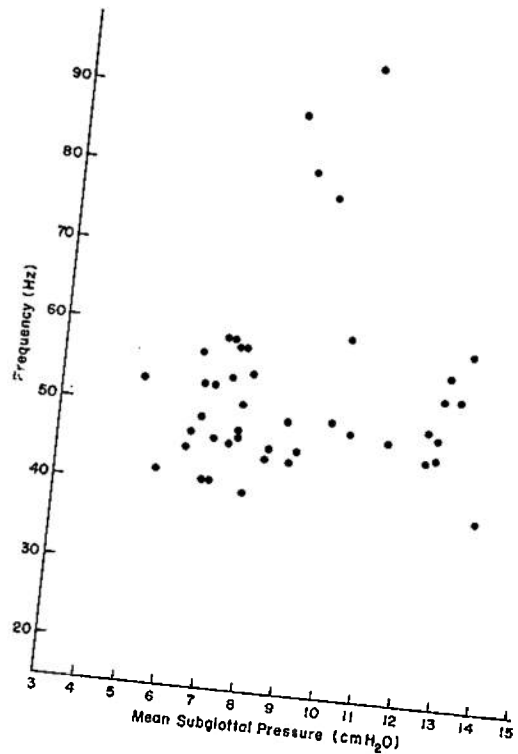


Fig. 3. Fundamental frequency as a function of the subglottal pressures produced by five subjects during sustained phonation of the vowel /a/. Each subject produced three samples at relatively slow, medium, and fast vocal fry rates.

Figure 4 indicates that the subglottal pressures for both treatment conditions, i.e., with and without the mouthpiece, increased as a function of the phonation condition in vocal fry. When the subglottal pressures for the two recording conditions are compared at any one phonation condition, it can be seen that the pressures produced while the subject was fitted with the mouthpiece were lower than when the mouthpiece was removed. The F ratio of 1.04 was less than the required value of 7.71 ($F_{.05; 1, 4}$) indicating that the effects due to insertion of the mouthpiece were not significant at the .05 level. Again, the effects due to phonation condition were significant at the .05 level, while the AB interaction was not statistically significant.

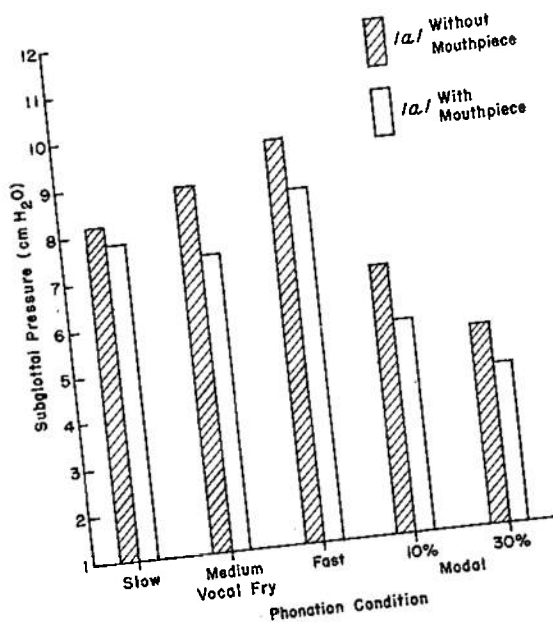


Fig. 4. Mean subglottal air pressure (cm H₂O) for phonation for /a/ with and without the air flow recording apparatus in the mouth at three vocal fry and two modal phonation conditions.

Air flow rate and mode of phonation.

Mean rate of air flow was obtained during phonation of /a/ at the five phonation conditions. The mean flow rates shown in Figure 5 for the five subjects at each condition were 36.64, 44.65, 44.04, 107.60, and 121.65 ml/sec. The extended lines from the data points indicate the range of flow rates at that condition for the combined group of subjects. From Figure 5, it is apparent that the mean rate of air flow is lower during vocal fry phonation than during modal phonation. It should be pointed out that although the ranges in air flow rate in vocal fry and modal phonation overlap, there was no overlap for any one subject's mean flow rates during the two types of phonation. Thus, subjects with relatively high vocal fry air flow rates had relatively high modal flow rates.

A one-way analysis of variance with repeated measures across subjects was performed to determine if there was a signifi-

cant difference among the flow rates for the five conditions of phonation. An F of 9.91 was obtained (F.05; 4, 6 = 3.01) indicating that air flow was significant at the tested level. When submitted to a Newman-Keuls test to determine what conditions accounted for the overall significance the data indicate that the flow rates between vocal fry and modal were significantly different; however, the flow rates within either the vocal fry conditions or modal range, respectively, were not statistically significant from each other. Thus, it may be concluded that the subjects in this study produced relatively low rates of air flow in vocal fry compared to those produced during modal range phonation.

IV. DISCUSSION

Prior to this study, no measures of subglottal pressure during vocal fry phonation have been reported. The finding of relatively large subglottal pressures, however, departs somewhat from a previous prediction of low pressures during vocal fry phonation by Hol-

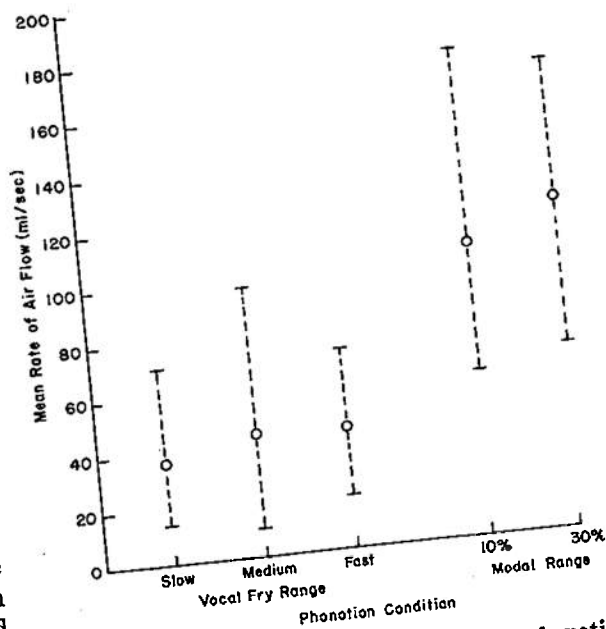


Fig. 5. Air flow rate as a function of phonation condition. Data points represent means for five subjects. Combined range of subjects for each condition indicated by dotted lines.

lien and others¹. Several factors may be considered to account for the unexpected high pressures.

Previous research has shown that the closed phase of the vocal fold waveform is generally longer than that during modal phonation. Thus, as Van den Berg³² suggests, when the folds are vibrating with a long closed phase, the subglottal pressures will be relatively large and produce a rapid opening of the folds. Van den Berg also suggested that if the area of the opening is small, air flow rate could be expected to be low. In vocal fry, the area of the opening appears to be temporally small with respect to the total period; therefore, pressure may build during the long closed phase and then force apart the apparently large vocal fold mass.

The high pressures may have also resulted from subjects attempting to phonate in a mode which they do not use often. That is, Kunze's results²² suggest that the subglottal pressure may increase as the subject deviates from the region at which he usually phonates. Thus, although subjects in this study practiced the tasks before the recordings were made, they were producing a type of phonation which departed from normal conversational speech and from the vocal region in which they usually phonate. The results of this study and of Kunze's show that the smallest subglottal pressures are in the frequency region usually used during conversational speech. Moreover, Kunze found pressures in the upper region of the modal range which were of the same general magnitude as those found for vocal fry in this study.

The flow rates obtained in this study and in McGlone's²⁷ were considerably lower in vocal fry than in modal phonation. Furthermore, the flow rates recorded during vocal fry were generally lower than those flow rates reported for falsetto phonation (Ishiki²⁵). Thus, it appears that the air flow associated with the production of vocal fry is less than that for most other phonational events. In this respect, the present findings support the prediction of Hollien, Moore, Wendahl, and Michel¹.

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Table I. Phonational ranges for the five subjects used in the present investigation. The measures are reported in the Hz used for the vocal fry and modal ranges.

Subject	Vocal Fry Range		Modal Range	
	Low	High	Low	High
1	32	81	73	523
2	22	75	82	440
3	24	90	73	523
4	28	92	98	330
5	28	62	65	494

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13. ABSTRACT The purpose of this study was to determine the subglottal pressures and rates of air flow produced during vocal fry phonation, a type of low frequency phonation characterized by a distinct popping sound. Simultaneous recordings of the voice signal, intratracheal air pressure, and rate of air flow, were obtained from five adult male subjects during three sustained phonations of the vowels /a/ and /i/ at three regions within their vocal fry range and two within their modal(mid)phonational range. The data were analyzed in terms of mean fundamental frequency, mean subglottal pressure, and mean rate of air flow. The results indicate that the subglottal pressures produced during vocal fry phonation are significantly greater than those produced at adjacent low frequencies in modal range. In addition, it was shown that as the repetition rate of vocal fry increases, subglottal pressure tends to increase. Subglottal pressure decreased between the 10 and 30 percent frequencies of the modal phonational range. The subglottal pressures produced during phonation of /a/ and /i/ at any one vocal fry or modal phonation condition were not significantly different; although those for the /i/ tended to be slightly larger than for /a/. Furthermore, there was no difference in the subglottal pressure accompanying phonation of the vowel /a/ as a result of inserting a mouthpiece into the subject's mouth to record air flow. Rate of air flow was found to be significantly lower in fry phonation and no relationship between flow rate and frequency in both ranges was found. The aerodynamic relationships indicate that during sustained vocal fry, subglottal pressure builds to open quickly the apparently massive vocal folds while the low flow rate may be related to the long closed phase of the vocal folds.			

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