SUBGLOTTAL PRESSURE MEASURES DURING VOCAL FRY PHONATION

By

THOMAS MURRY

A DISSERTATION PRESENTED TO THE GRADUATE COUNCIL OF
THE UNIVERSITY OF FLORIDA
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1969

ACKNOWLEDGMENTS

The author expresses sincere gratitude to his committee chairman Dr. Donald Dew for his continued support and encouragement during the preparation and execution of the experiment and also throughout the author's training program at the University of Florida. Further gratitude is expressed to the members of the dissertation committee for their suggestions and contributions to the ideas expressed herein. Special thanks are given to the subjects who willingly submitted to the procedures of the experiment.

The author wishes to acknowledge the invaluable support from the faculty, staff, and students of the Communication Sciences Laboratory and to the staff of the Bronchopulmonary Laboratory, J. Hillis Miller Health Center. The author is especially indebted to Mr. Robert Idzikowski for his assistance in preparing the instrumentation for the study, to Dr. J. O. Harris and Mrs. Joyce Fedik for their assistance during the experimental sessions, and to Drs. Harry Hollien and John F. Brandt for their constructive criticism provided during the preparation of preliminary drafts of this report.

This research was supported by the National Institutes of Health grants NB-05475 and NB-06459.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION AND STATEMENT OF PROBLEM

Introduction

Recently, Hollien and Michel (1968) demonstrated that vocal fry can be appropriately classified as one of the three frequency ranges used by normal speakers during phonation. Each of these ranges, falsetto, modal (or mid-range),[1] and vocal fry, appears to have distinctive characteristics with regard to its 1) production, 2) acoustic wave form, and 3) perceptual attributes. The absolute fundamental frequencies of the ranges will vary from speaker to speaker, but for any single speaker, falsetto is produced with the highest fundamental frequencies, modal is produced in the middle frequency

---

[1]The mid-range of the total phonational range is sometimes considered to be the modal register (Morner, Franeson, and Fant, 1963). As noted by Hollien and Michel (1968), however, the term "voice register" appears to have no adequate, accepted definition. In fact, various investigators have divided the total phonational range into as few as one and as many as five "voice registers" (Morner, Franeson, and Fant, 1963). It was not the purpose of the research to provide a description of the term "voice register"; rather, the intent was to describe certain relationships which occur in vocal fry, a mode of phonation perceptually described as a quasi periodic series of relatively distinct pulses.

range, and vocal fry is produced in the lowest range of fundamental frequencies.

Because vocal fry has been recognized only recently as a normal phonatory range (Hollien, Moore, Wendahl, and Michel, 1966) which appears to occur routinely during speech, it is of particular interest to the scientist. There have been several investigations concerning the description and perception of fry (Coleman, 1963; Wendahl, Moore, and Hollien, 1963; Hollien and Michel, 1968; Michel and Hollien, 1968; Hollien and Wendahl, 1968); information concerning the operation of the laryngeal structures during vocal fry phonation, however, is somewhat lacking. Specifically, previous investigations of vocal fry have provided information concerning the approximate range of vocal fold repetition rates. For example, in a recent investigation by Hollien and Michel (1968), the phonational ranges of 12 males and 11 females were found to be from two to 78 pulses per second.[2] This study confirms the results of earlier investigations reporting on the approximate range of vocal fry repetition rates (Michel and Hollien, 1968; McGlone, 1967) and

---

[2]When the term, "pulse," is used, it refers to a function which makes one or more excursions from a baseline and which has a finite baseline time (Hubbs, 1966).

suggests that fry is characterized by fundamental frequencies lower than those in the modal register.

Hollien and Wendahl (1968) have also reported that subjects can accurately match the repetition rate of vocal fry pulse patterns to electronically produced pulses occurring at low frequencies. Thus, in fry there appears to be sufficient periodicity in the signal for listeners to perceive it as having a low fundamental frequency.

Although low fundamental frequencies are characteristic of vocal fry phonation, Coleman (1963) reported that the damping of the wave rather than its repetition rate was the important factor in its perception. Using an electronic laryngeal analog to vary the damping factor, he reported that when the damping factor reached a critical value, fry was always perceived; when the damping factor was less, fry was not perceived regardless of the frequency. Wendahl, Moore, and Hollien (1963) have also demonstrated that the vocal fry acoustic wave forms of human productions show high damping. Having examined a large number of phonellographic tracings, they found fry to be characterized by a highly damped wave form in addition to its low frequency. It appears, therefore, that vocal fry is a distinct mode of phonation with relatively low fundamental frequencies and a wave form which is highly damped.

In an investigation of glottal wave forms, Timke, Von Leden, and Moore (1958), also provide data which would support the contention that the vocal fry wave form is highly damped. Using high speed motion picture photography, they found the vocal fry glottal wave form to be the result of a pulse-like opening and closing of the folds followed by a long closed phase. Indeed, some examples of fry phonation have been observed (Fant, 1964; Coleman, 1968) which consist of a double or triple pulse followed by the long closed phase. Wendahl, Moore, and Hollien (1963) report that while these patterns were found in their phonellographic tracings, the most common vocal fold vibratory pattern in vocal fry is one of a single glottal pulse followed by the characteristically long closed phase.

Although the production of modal range phonation has been extensively investigated, the operation of the laryngeal mechanism during vocal fry has not been specified. This lack of research may be attributed in part to the misconception that vocal fry was considered a pathological condition which occurred only infrequently. Clearly, although vocal fry may be pathological if used extensively, it does exist as a product of the normal larynx as pointed out previously. If regarded as a normal phonatory event, then the mechanism of fry production may be explained within a framework of other types of normal phonation, namely the myoelastic-aerodynamic theory of phonation (Van den Berg, 1958).

Investigations of the voice produced during modal phonation have shown frequency to be highly correlated with vocal fold length,[3] mass, and thickness[4] and the subglottal pressures needed to maintain vocal fold movement (Kunze, 1962). While considerable data have been presented showing the relationship between vocal fold length and fundamental frequency of phonation in the modal range, it has been shown that the length of the folds does not appear to vary as a function of the repetition rate in fry (Hollien, Damste, and Murry, 1969).

Investigations of vocal fold thickness (see footnote four) have generally shown that, as the fundamental frequency of phonation decreases, the thickness of the vocal folds increases. Although the reports of the thickness of the vocal folds during fry as yet are predominantly qualitative, they indicate that during vocal fry phonation the folds appear to be rather thick but not necessarily tense. These observations were noted by Coleman (1968) from examination of high speed motion pictures, by Hollien, Damste, and Murry (1969) from a strictly subjective comparison of lateral x-rays

---

[3]Irwin, 1940; Brackett, 1947; Sonninen, 1954, 1956; Hollien, 1960; Hollien and Moore, 1960; Hollien, 1962; Wendler, 1964; Damste, Hollien, Moore, and Murry, 1968.

[4]Hollien and Curtis, 1960; Hollien, 1962a, 1962b; Hollien, Coleman, and Moore, 1968.

and from laminagraphs (Hollien, 1968) taken during modal and fry phonation.

Most of the data concerning the aerodynamic forces present during phonation exist for modal range phonation. Kunze (1962, 1964), Isshiki (1964), and Perkins and Yanagihara (1968) investigated mean rate of air flow over a wide range of frequencies and found a positive relationship between air flow rate and intensity. These investigators found air flow rate to have little or no relationship to the fundamental frequency of phonation. Additional findings by Kunze (1962) demonstrated the importance of the air flow measuring system; he has shown that the absolute values of flow rates are significantly lower when a respirometer is used in place of a pneumotachograph.

Air flow rates during sustained phonation of vocal fry have been obtained by McGlone (1967) using a respirometer. 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. A Pearson Product-Moment Correlation Coefficient was carried out for the two sets of measures and found to be .26. These results for fry phonation, like those obtained for higher frequency phonation, did not demonstrate any systematic relationship between air flow rate and repetition rate.

As yet, there are no experimental results of the subglottal pressures produced during vocal fry phonation.

Several investigators have obtained subglottal pressure measures for low frequency modal phonation of the vowel, /a/ (Van den Berg, 1956; Isshiki, 1959; Ladefoged, 1962; Kunze, 1962); however, their results appear to conflict. For example, Van den Berg (1956) reported a mean subglottal pressure of 10 cm H_2O for phonation at 145 H_z as compared to 9 cm H_2O for phonation at 97 H_z. Isshiki (1959) found an average pressure of 9 cm H_2O for sustained phonation at 123 H_z and 5.5 cm H_2O for phonation at 98 H_z. While Ladefoged's (1962) results show a similar trend, Kunze (1962) noted that as the subject produced tones below or above the 30 percent point of his phonational range, subglottal pressure increased. Thus, the only implication appears to be that frequency increases as a function of subglottal pressure over the upper portion of the phonational range. Due to sampling techniques, the use of a single vowel, and procedural considerations,[5] however,

---

[5]The measures reported by Ladefoged and his associates (Draper, Ladefoged, and Whitteridge, 1957, 1959; Ladefoged, Draper, and Whitteridge, 1958; Ladefoged (1962) are somewhat higher than those reported by Van den Berg (1956) and Isshiki (1959). This is, as Kunze (1964) has shown, due to the fact that Ladefoged's results are based on estimates of subglottal pressure obtained from recordings of the intraesophageal pressure rather than intratracheal pressure measures. It has been previously demonstrated (Fry, Stead, Ebert, Lubin, and Wells, 1952; Mead and Whittenberger, 1953) that recordings of intraesophageal pressure consist of the intratracheal (airway) pressure which drives the folds plus the pressure required to overcome the elastic resistance of the lungs. Since this latter resistance is not constant over the expiratory cycle, it appears that intraesophageal pressure is not a valid estimate of subglottal pressure.

this relationship is not clear, especially at the low end of the modal frequency region.

Kunze's (1962) subglottal pressure measures based upon recordings of the vowel /a/ by 10 subjects at five points along their phonational range appear to be the most comprehensive of those reported. He found that from the 90 percent to 10 percent points of the subjects phonational range (excluding vocal fry), subglottal pressure decreases as the fundamental frequency decreases except at the subjects' 10 percent point. In addition, and perhaps of major significance, Kunze demonstrated the importance of obtaining direct (intratracheal) measures of subglottal pressures (see footnote five) rather than indirect estimates of pressure from an esophogeal balloon. He concluded that ". . . there is little doubt that intratracheal pressure measures provide the only satisfactory estimates of subglottal pressure under conditions of sustained phonation and during connected speech."

Statement of the Problem

Previous studies of the aerodynamic factors contributing to laryngeal operation have been confined predominantly to the middle and upper portions of the phonational range and have demonstrated that 1) increases in subglottal pressure are usually accompanied by increases in the fundamental frequency of phonation, 2) subglottal pressure is directly related to vocal intensity, 3) air flow appears to be related to vocal intensity, and 4) there is no systematic relationship between the fundamental frequency of phonation and air flow rate.

To date, only the variable of air flow rate has been examined during vocal fry. Specifically, air flow was found to be significantly lower in vocal fry than in modal phonation and to have no relationship to fundamental frequency of phonation (McGlone, 1967). In order to understand the operation of the laryngeal mechanism during vocal fry, it would appear necessary to examine both air pressure and air flow rate as they relate to changes in the repetition rate and vocal intensity of vocal fry phonation.

The major purpose of this study was to determine if the subglottal pressures and rates of air flow produced during vocal fry differ from those in the mid-phonational range. A second purpose was to investigate the relationship between the fundamental frequency of phonation of vocal fry and both subglottal air pressure and rate of air flow. Finally, consideration was given to the observed relationships between variations in vocal intensity and the subglottal pressure/ air flow data.

CHAPTER II

PROCEDURES

The plan of this study was to obtain simultaneous measures of the intratracheal air pressure, air flow rate, and sound pressure during vocal fry and mid-range phonation from five adult males. These measures were obtained during sustained phonation of the vowels /a/ and /i/. These vowels which represent two extreme supraglottal configurations were chosen to determine if varying the supraglottal structures affects subglottal pressures. The samples were produced at three vocal fry and two mid-range fundamental frequencies.[1]

Equipment

A block diagram of the instrumentation employed in the present study is shown in Figure 1. While the subject phonated in a supine position, subglottal pressure was measured directly through a hypodermic needle inserted between the first and second tracheal rings, air flow was measured through a pneumotachograph connected to a mouthpiece held in place by

[1]In order to avoid considerable confusion in the discussion of the mode of phonation, the term "fundamental frequency" will be used throughout the remainder of this study to refer to the quasi periodic laryngeal signal produced during vocal fry and mid-range phonation. While this term departs somewhat from standard acoustic terminology (Hubbs, 1966), it appears to be descriptive of the frequency of the repetitive wave forms found both in vocal fry and mid-range phonation.

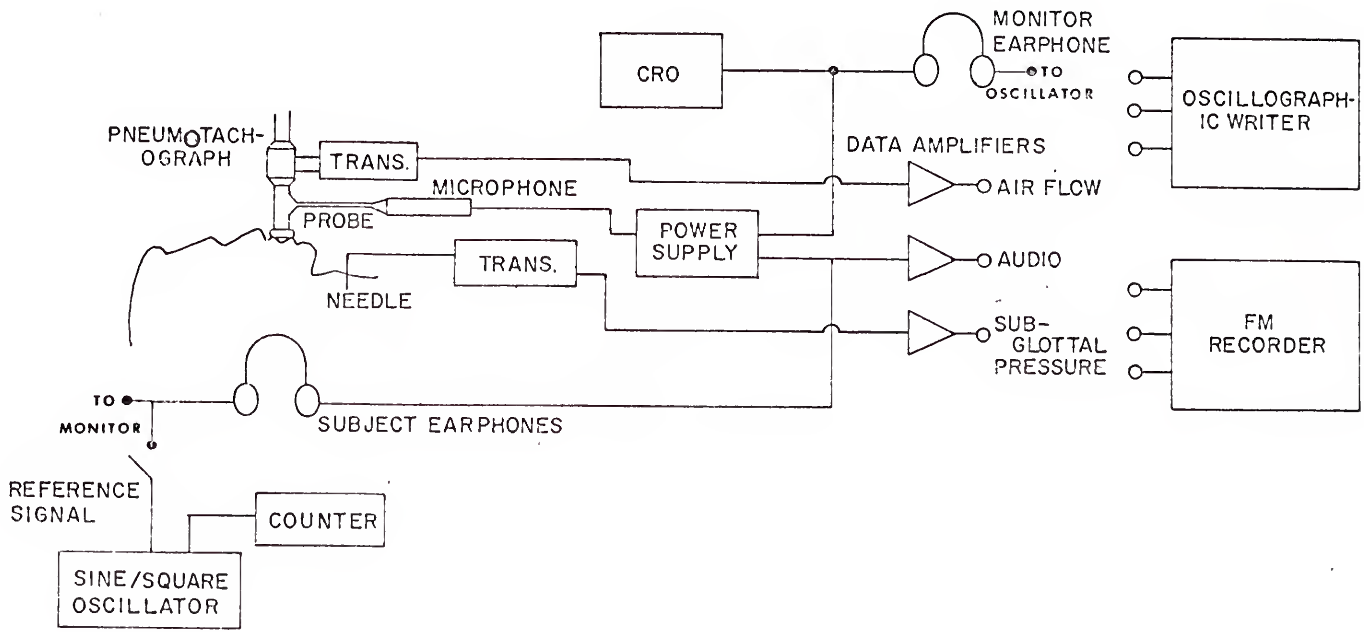

Figure 1. Block diagram of equipment used to provide the reference signals, record the pressure, flow and voice signals, and monitor subjects' output.

a flange fitting between the lips and teeth, and sound pressure was measured with a microphone and probe tube inserted into the connecting tube of the pneumotachograph. Following amplification by separate channels of a data amplifier, each of the three signals was recorded on both an oscillographic writer and an FM magnetic tape recorder.

For monitoring phonation, the 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 frequency of phonation; the reference signal was generated by a sine-wave oscillator for mid-range frequencies while a square-wave generator provided reference signals for vocal fry.

Instrumentation for measuring and calibrating subglottal pressure

After applying a local anesthetic (one percent xylocaine) to the laryngeal area, a physician inserted an 18 gauge hypodermic needle (3.5 inches long with an inside diameter of .033 inches) 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 a Statham PM 131 TC differential pressure 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. Kunze (1964) and Perkins and Yanagahara (1968) have shown that direct pressure recordings made in this manner provide consistent measures of the intratracheal pressure driving the folds.

The intratracheal pressure measuring system was calibrated daily by reference to a U-tube manometer scaled in centimeters of water (cm H_2O). The manometer was connected to the pressure transducer and associated oscillographic writer by means of a Y-valve having one end open to the atmosphere and the other attached to a syringe. By applying a steady pressure with the syringe, a specific displacement of water in the manometer could be calibrated with a specific pressure change shown on the oscillographic writer. By this method it was found that the transducer and its system were linear within the levels needed in the present study.

Instrumentation for measuring air flow

Air flow measurements were made by a pneumotachograph which operates according to the Law of Poiseuille. That is, along a rigid tube, there is a decrease in pressure which is proportional to the velocity of flow per unit length when the flow is laminar (Rossier, Buhlmann, and Wiesinger, 1954). Therefore, continuous recording of the pressure differences between two points yields a function which, when integrated, indicates the volume of air moved per unit of time. In the present study, air flow was recorded by connecting a Fleish No. 0 pneumotachograph to a mouthpiece 2.12 inches in length and held in place by a flange fitting between the lips and teeth. The pneumotachograph was connected through a Statham PM 97 pressure transducer to the data amplifier and recording systems. This device, used with a noseclip, 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 (Isshiki, 1959; Kunze, 1962; Hardy, 1965).

Calibration of the air flow recording system was accomplished by passing a known flow rate produced by a variable speed Emerson RJV-192 vacuum cleaner through a Fisher-Porter rotameter and to the transducer. The rotameter recorded the flow rate in liters per second; thus, the deflections on the oscillograph were converted directly to milliliters of air flow per second (ml/sec).

Sound pressure measurements

Relative intensity levels[2] during the vocal fry conditions were measured by a Bruel and Kjaer 4134 one-half inch condenser microphone with a probe tube six centimeters long and an inside diameter of .2 mm. The frequency response of the probe tube and microphone was found to be ± 3 dB over a range of 20-1000 Hz. The microphone probe was fitted into an insert in the wall of the pneumotachograph and was connected to its associated Bruel and Kjaer 2801 Microphone Power Supply. The signal in turn was fed to one channel of the data recorder, the FM tape recorder, and a Tektronix 310A oscilloscope. The oscilloscope provided the subject and the experimenter with a visual trace of the phonation which was used to maintain constant intensity for each phonation condition.

Monitoring devices

In order to maintain a constant frequency during phonation, the subject was provided with a reference signal produced by a General Radio 1313A Oscillator and presented through a Telephonics TDH 39 earphone, as shown schematically

---

[2]The intensity levels for the vocal fry conditions were not predetermined since it was observed in a pilot study that vocal intensity, measured in front of the mouth tended to increase as the repetition rate increased.

in Figure 1. The accuracy of the generator was verified by a Hewlett Packard 5214L Preset Counter. The frequency settings were determined from the information obtained from the subjects' phonational ranges (Appendix A). The vocal fry reference signals were square waves set at slow, medium, and fast frequencies of the subject's fry phonational range. The reference signals for the 10 and 30 percent frequencies of the modal range were sine waves set at the predetermined frequencies for each subject.

Experimental Procedure

Subjects

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

Phonational ranges

Prior to the experimental task, each subject's modal and vocal fry phonational ranges were determined. The modal range was obtained in the traditional fashion by having each subject sing up and down the musical scale until he produced his highest and then his lowest sustainable notes. In order to monitor his production, he was instructed to match a series of pure tones presented at tone intervals. The subject and the experimenter acted as judges to determine which tones represented the extremes of his modal range. The highest and lowest frequencies produced by the subject and agreed upon by the experimenter were considered as the modal phonational range boundaries.

The vocal fry range was determined by a procedure similar to that described by Hollien and Michel (1968). 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 four-second sample was recorded on magnetic tape. To measure repetition rate, tape loops of the samples were played through a General Radio 1900A Wave Analyzer coupled to a Hewlett Packard 5214L Preset Counter. The wave analyzer was set to the tracking generator mode having a three-cycle bandwidth. When the largest deflection appeared on the voltmeter, the frequency at that point was recorded from the counter. The mid and fry phonational ranges of all subjects are shown and discussed in Appendix A.

<u>Tasks</u>

After administering a local anesthetic to the laryngeal area, a physician inserted the hypodermic needle for recording the intratracheal pressure. The needle was connected to the transducer and the subject was given ample time to adjust to the experimental apparatus. Each subject was then instructed to produce three samples of the vowels /a/ and /i/ at slow, medium, and fast repetition rates within 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 and the subject was asked to produce samples of the vowel /a/ at the three vocal fry and two modal range frequencies. All recordings were made while the subject was in the supine position. A set of earphones presented the reference signal at one ear while the subject monitored his vocal output at the other ear. Thus, in the first series of recordings, subglottal pressure was recorded during phonation of two vowels at five frequencies. In the second series, subglottal air pressure and air flow were recorded for the vowel /a/ only at the five frequency conditions since it appeared that recordings of /i/ would be greatly distorted in phonemic quality or would result in air leakage around the mouthpiece. Appendix B contains the recording itinerary followed throughout.

Data Analysis

For each subject, frequency and pressure recordings were made for the vowels /a/ and /i/ at three frequency regions in vocal fry and two in the modal range. During a separate recording period, the frequency, pressure, and air flow were obtained for the vowel /a/ only at five frequency regions. It was necessary to convert the outputs of the multitrace oscillographic writer into numerical values (Appendix C) to estimate the actual subglottal pressure and rate of air flow. This was accomplished by measuring the pressure shifts produced on the oscillographic writer at 100 millisecond intervals for three seconds and converting the values to centimeters of water for subglottal air pressure and milliliters of air per second for air flow using the appropriate calibration factors previously obtained. For each phonation a mean and standard deviation was computed. The means of three samples at a particular phonation condition were computed for frequency, subglottal air pressure, rate of air flow, and relative intensity[3] and used as the criterion measures.

The fundamental frequency data were obtained from the Honeywell FM tape recorder. The recorder was slowed by a factor of eight and played through a Sanborn 150-1300D Dynagraph.

---

[3]The relative intensity levels were obtained by recording a two-volt sine wave on the tape recorder and playing it back through a Bruel and Kjaer 2112 Audio Frequency Spectrometer which acted as an attenuater. The output or the spectrometer was coupled to a Bruel and Kjaer 2305 Graphic Level Recorder which recorded the reference signal at mid-scale with a 50 dB potentiometer. The measures reported are relative to this scale value rather than to the actual 2-volt signal. The use of the scale values eliminates the large negative dB values.

Wave-to-wave measurements of the output of each sample were made by measuring the wave from peak-to-peak, dividing this by eight times the speed of the dynagraph to get the period. Using the formula $F = \frac{1}{T}$, period measures were converted to frequency in Hz.

Two analyses of variance with repeated measures were performed on the subglottal pressure measures to determine the effects of vowels, the mouthpiece, and the frequency of phonation on the subglottal pressures (Lindquist, 1953). The first was a frequency-by-vowel-by-subject anaylsis to determine the effects of the phonation condition and vowel. The second tested the effects of phonation condition and addition of the mouthpiece on subglottal pressure. Since only one vowel was used during the pressure and flow recordings, a one-way analysis of variance with repeated measures was performed on the air flow data to determine the effects of frequency changes on air flow rate. Thus, it was possible to test differences in pressure for effects due to frequency, vowel, and insertion of the mouthpiece and in air flow for effects due to frequency of phonation.

To determine the relationship between the actual repetition rate and subglottal pressure during vocal fry phonation, a Pearson Product-Moment Correlation Coefficient was computed for the variables of repetition rate and subglottal pressure. Similarly, a Pearson Product-Moment Correlation Coefficient was computed between repetition rate in vocal fry and rate of air flow.

CHAPTER III

RESULTS

The major purpose of this study was to determine if the subglottal pressures and rates of air flow produced during vocal fry phonation differ from those produced in modal range phonation. This study also investigated the relationships of both subglottal air pressure and rate of air flow with a) fundamental frequency and b) vocal intensity. In order to accomplish these purposes, simultaneous recordings of the intratracheal air pressure, air flow, and sound pressure were obtained from five subjects phonating the vowels /a/ and /i/ at five fundamental frequency regions, three in the vocal fry and two in the modal range. Three samples at each experimental condition were obtained; the criterion measures were the mean frequency, mean subglottal pressure, mean rate of air flow, and average relative intensity for three samples in each condition.

It should be noted that the subglottal air pressures and mean rates of air flow obtained in the present study varied from subject to subject as well as between successive samples produced by the same subject. For example, subject two was found to have mean subglottal air pressures which were higher than those of most other subjects; however, the frequencies at which he was phonating were similar to the other subjects. Moreover, examination of the raw data ahowed that subject two had little sample-to-sample variation in comparison to subject one. The reader should be aware of the existence of the variability found in this as well as other investigations (Kunze, 1962) when interpreting the present data.

Subglottal Pressure During Vocal Fry

Relationship of subglottal pressure to phonation condition and vowel

The mean subglottal pressures for the vowels /a/ and /i/ produced at three vocal fry and two modal frequency regions of the subjects' ranges are shown in Figure 2. Figure 2 clearly indicates that the subjects' subglottal air pressure was greater in vocal fry than in the two modal range conditions. Moreover, there were no reversals in this trend at any phonation condition. From Figure 2 it can also be seen that as subjects increased frequency of phonation in vocal fry, the subglottal pressure increased. In the modal range conditions, however, the subglottal pressures decreased as the subjects' frequency increased from the 10 percent

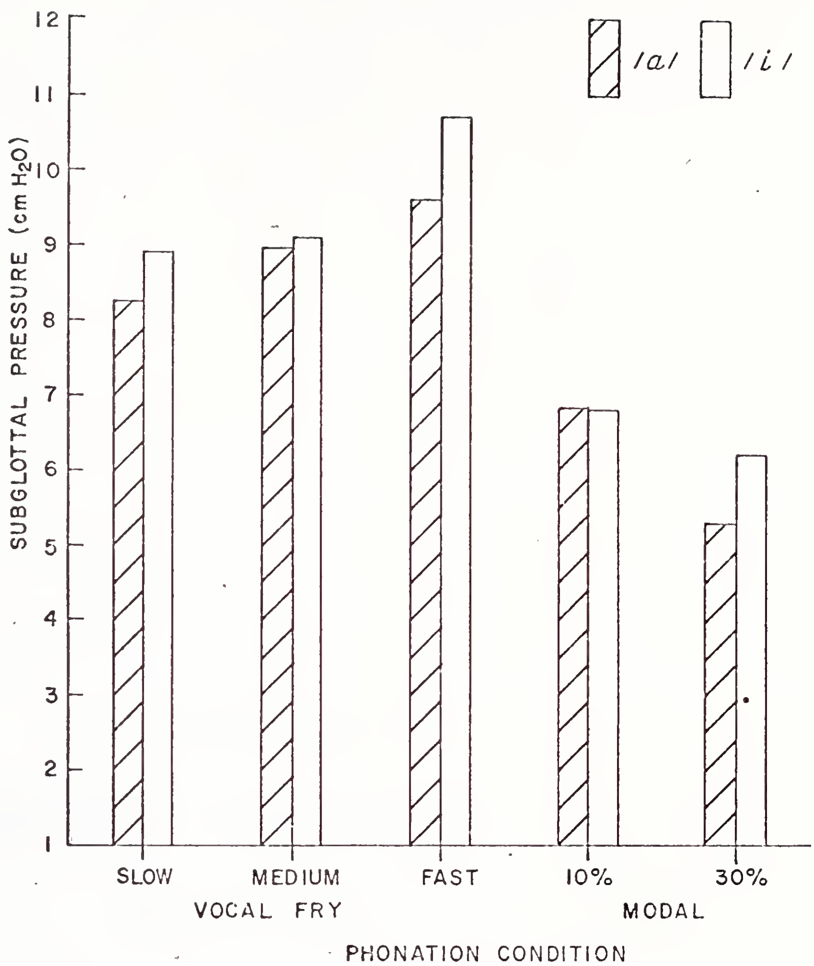

Figure 2. Subglottal pressure (cm H_2O) plotted for the vowels /a/ and /i/ during three vocal fry and two modal phonation conditions.

region[1] of their modal phonational range. In vocal fry, the overall mean increase in subglottal pressure from the slow repetition rates to the fast rates was statistically significant at the five percent level. In view of the variability exhibited by the subjects during the production of the modal range frequencies, however it can only be shown that as the subjects increased their fundamental frequency, subglottal pressures decreased significantly as the fundamental frequency approached the 30 percent region of a subject's modal phonational range.

Figure 2 also shows that the subglottal pressure trends which were found for the /a/ were similar to those found for /i/; although the values for /i/ were higher in all but one condition, the differences were not significant.

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 (Lindquist, 1953) was performed. The results of this analysis are presented in Table 1. The effect of phonation condition was significant at the .05 level;

---

[1]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.

Table 1. Summary of three-way analysis of variance to determine the effects of vowels and phonation conditions upon the subglottal pressures.

Source of Variation	SS	df	MS	F
A Phonation condition	125.38	4	31.35	4.52*
B Vowels	4.33	1	4.33	1.56
S Subjects	81.47	4	20.37	
AB	1.95	4	.49	.53
AS	110.51	16	6.91	
BS	11.08	4	2.77	
ABS	14.67	16	.92	
Total	349.39	49		

*Significant at the .05 level of confidence ($F_{.05,4,16} = 3.01$, $F_{.05,1,4} = 7.71$).

the effects due to vowels and the AB interaction were not statistically significant at the tested level.

To determine which of the phonation conditions accounted for the overall significance of this effect, the Newman-Keuls test of treatment differences following an overall significant F-ratio was applied to the data. This statistic tests the difference between any number of means arranged in increasing order of magnitude while maintaining the level of significance equal to alpha. The results of this test presented in Table 2 indicate that all phonation conditions were significantly different from each other. That is, the pressures in all samples of vocal fry were significantly greater than the pressures in all samples of mid-range phonation. Furthermore, the matrix shows that the pressures at the 10 percent modal frequency were significantly greater than those at the 30 percent region and also that the pressures at each of the three fry frequency regions were significantly different from each other.

Effects of mouthpiece and phonation condition upon subglottal pressure

As described previously, subglottal pressures for the vowel /a/ were recorded when the subject had a mouthpiece inserted for the purpose of recording air flow rate and when the mouthpiece was not inserted. Figure 3 presents the

Table 2. Comparison of subglottal pressures at each phonation condition. The marginal values contain the sum of the subglottal pressures for both vowels at each phonation condition. The values in the matrix represent the differences between each marginal pair.

		30% Modal	10% Modal	Slow Fry	Medium Fry	Fast Fry
		89.39	97.04	124.68	126.51	145.01
30% Modal	89.39		13.65*	41.29*	43.12*	61.62*
10% Modal	97.04			27.64*	29.47*	47.97*
Slow Fry	124.68				1.83	20.33*
Medium Fry	126.51					18.50*

*Significant at the .05 level of confidence. Critical difference = $t_{.05}\ (2MS_{as/n})^{\frac{1}{2}}$.

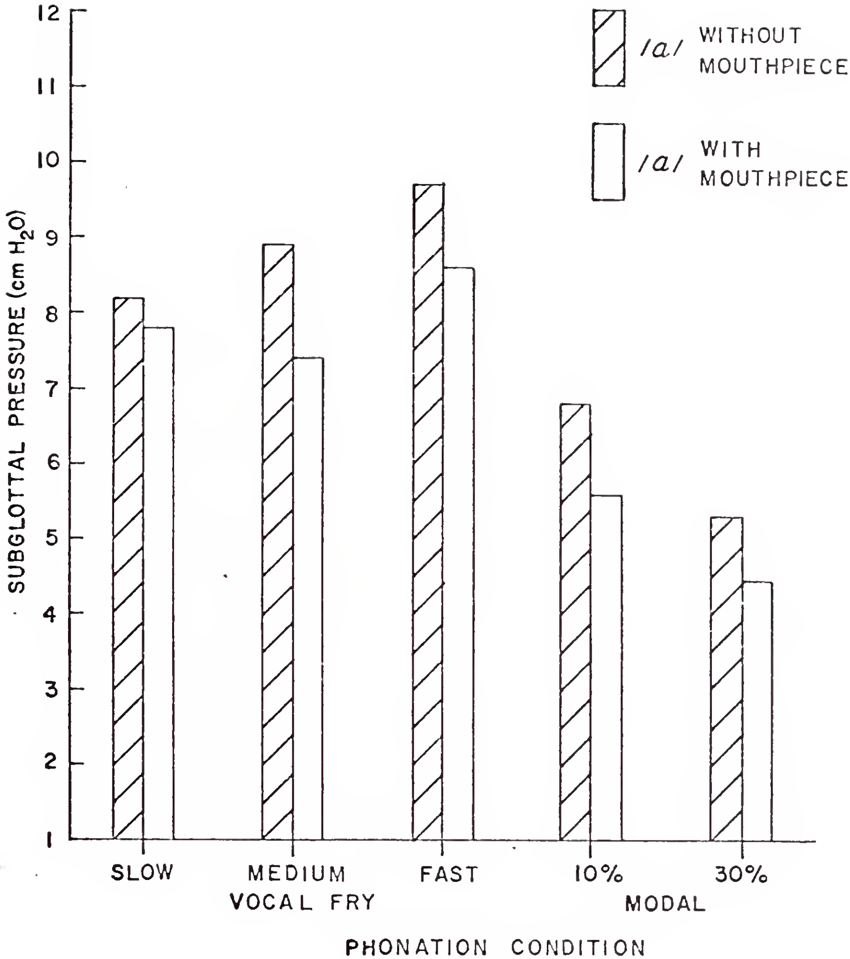

Figure 3. Mean subglottal air pressure (cm H_2O) for phonation for /a/ with and without the air flow recording apparatus in the mouth at three vocal fry and two modal phonation conditions.

results for the mean subglottal pressures for the /a/ under these two conditions plotted as a function of phonation condition. Figure 3 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. The subglottal pressures in the modal range were lower than those in vocal fry and tended to decrease as the subjects increased frequency of phonation. 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 mouthpeice were lower than when the mouthpiece was removed. Thus, it appears that the addition of the mouthpiece for recording air flow rate caused a reduction in the subglottal pressures.

An analysis of variance was performed to determine if the changes in pressure as a function of the two variables was statistically significant; Table 3 summarizes this analysis. The effects due to insertion of the mouthpiece were not significant at the .05 level. The effects due to phonation condition were significant at the .05 level; the AB interaction was not significant at the tested level.

The Newman-Keuls test was applied to the data to determine which of the phonation conditions accounted for the

Table 3. Summary of three-way analysis of variance to determine the effects of the mouthpiece and phonation conditions upon subglottal pressure.

Source of Variation	SS	df	MS	F
A Phonation condition	99.73	4	24.93	7.16*
B Mouthpiece	8.00	1	8.00	1.04
S Subjects	96.00	4	24.00	
AB	3.69	4	.92	.52
AS	55.79	16	3.48	
BS	30.63	4	7.66	
ABS	28.08	16	1.76	

*Significant at the .05 level of confidence ($F_{.05,4,16} = 3.01$, $F_{.05,\ 1,4} = 7.71$).

overall significance of this effect. Table 4 presents the results of this test. It can be seen that all fry pressures were significantly different from those in the modal range. The pressures within each range, however, were not statistically significant from each other at the .05 level.

Thus, it was found that subglottal pressure during vocal fry is greater than during modal range phonation. It was also found that subglottal pressure increases as a function of frequency in vocal fry over the range of frequencies produced by the five subjects in this experiment. Subglottal pressure decreased from the 10 to 30 percent frequencies in the modal range. Furthermore, the pressures produced during phonation of /i/ in the vocal fry and modal frequency ranges are greater than the pressures produced during phonation of /a/; however, this difference was not statistically significant. Finally, the insertion of a mouthpiece for recording air flow rate has no statistically significant effect upon the pressures produced while phonating /a/; however, the pressures produced under this condition are less than when the mouthpiece is not in place.

<u>Air flow rate and mode of phonation</u>

Mean rate of air flow was obtained during phonation of /a/ at the five phonation conditions. The results of these measures are shown in Figure 4. In Figure 4, mean rate of

Table 4. Comparison of subglottal pressures at each phonation condition. The marginal values contain the sum of the subglottal pressures for both mouthpiece conditions at each phonation condition. The values in the matrix represent the differences between each marginal pair.

		30% Modal	10% Modal	Slow Fry	Medium Fry	Fast Fry
		54.40	63.00	80.10	81.20	91.40
30% Modal	54.40	1.00	8.60	25.70*	26.80*	37.00*
10% Modal	63.00		1.00	17.10*	18.20*	28.40*
Slow Fry	80.10			1.00	1.10	11.30
Medium Fry	81.20				1.00	10.20

*Significant at the .05 level of confidence. Critical difference = $t_{.05}$ $(2MS_{as/n})^{\frac{1}{2}}$.

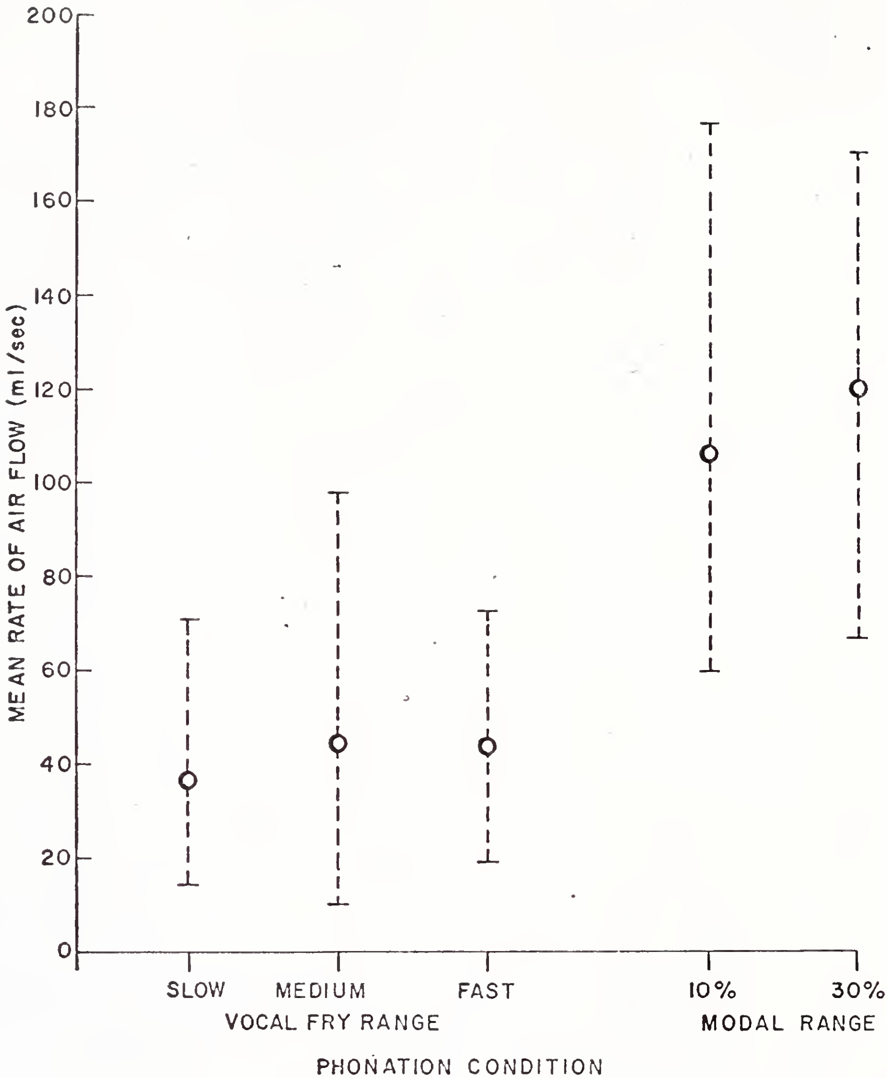

Figure 4. Air flow rate as a function of phonation condition. Data points represent means for five subjects. Combined range of subjects at each condition indicated by dotted lines.

air flow is plotted as a function of the three vocal fry and two modal range frequencies of phonation. The extended lines from the data points indicate the range of air flow rates at that condition for the combined group of subjects. From Figure 4, it is apparent that the mean air flow rate during vocal fry phonation is lower than during modal range phonation. While there appears to be an increase of flow rate as frequency increases, the ranges obtained from the subjects tend to mask this trend. It should be pointed out that although the combined air flow ranges in vocal fry and modal phonation overlap, there was no overlap within any one subject's mean flow rates during the two types of phonation. That is, subjects with vocal fry flow rates relatively greater than the mean flow rates also had relatively greater modal flow rates than the overall means at those two conditions. The mean flow rates for each subject can be found in Appendix C.

A one-way analysis of variance with repeated measures across subjects (Winer, 1962) was performed to determine if the flow rates for the five conditions of phonation were significantly different. Table 5 summarizes the analysis indicating that the overall F-ratio 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 at the .05 level, however; the

Table 5. Summary of the analysis of variance for air flow as a function of phonation conditions.

Source of Variation	Sum of Squares	dF	Mean Square	F_{obt}
Between Subjects	18.63	4	4.66	
Within Subjects	76.84	20	3.84	
Phonation Conditions	54.69	4	13.67	9.91*
Error	22.15	16	1.38	

*Significant at the .05 level of confidence ($F_{.05,4,16} = 3.01$).

flow rates within the vocal fry and modal conditions were not statistically significant from each other. These results are summarized in Table 6. It may be concluded that the subjects in this study produced relatively low pressures in vocal fry compared to those produced during modal range phonation.

Variations in Air Pressure and Flow in Vocal Fry Phonation

Another purpose of this study was to examine the mean air pressure and air flow rate as they relate to repetition rate and vocal intensity during vocal fry. As described previously, subglottal pressures and flow rates were obtained for three samples at each vocal fry condition. The data are shown in Appendix D.

It should be noted that during the experiment, subjects failed to produce repetition rates at the extremes of their fry phonational ranges which were obtained prior to the experiment. For example, the pre-experimental vocal fry ranges (shown in Appendix A) varied from 22 to 92 H_z while the experimental values ranged only from 40 to 90 H_z. Nonetheless, as may be seen in Appendix D, relatively fast, medium, and slow repetition rates were obtained for each subject.

Relationship between repetition rate and subglottal pressure

In order to investigate the relationship between the actual repetition rates and subglottal pressures produced by

Table 6. Comparison of the air flow rates at each phonation condition. The marginal values contain the sum[1] for each phonation condition. The values in the matrix represent the difference between each marginal pair.

		Slow Fry 7.50	Fast Fry 9.02	Medium Fry 9.15	10% Modal 22.05	30% Modal 24.93
Slow Fry	7.50		1.52	1.65	14.55*	17.43*
Fast Fry	9.02			.13	13.03*	15.91*
Medium Fry	9.15				12.90*	15.78*
10% Modal	22.05					2.88

*Significant at the .05 level of confidence. Critical difference = $t_{.05}(2MS_{as}/n)^{\frac{1}{2}}$.

[1]The values represent the raw score analog measures. They may be converted to air flow rates in milliliters per second by multiplying each value by 24.6.

the subjects in this experiment, a Pearson Product-Moment Correlation Coefficient (Hays, 1963) was computed between subglottal pressure and repetition rate. A correlation of .27 was found for this relationship, which when tested for significance using a t-ratio, was found to be not significant at the .05 level.

Relationship between repetition rate and air flow rate

A Pearson-r was computed between repetition rate and mean rate of air flow during sustained phonation of the vowel /a/. An r equal to -.29 was obtained and found to be non-significant at the .05 level.

Intensity variations related to subglottal air pressure and air flow rate

In view of the large variability in the subglottal pressure measures and the variability observed in the relative intensity measures, an investigation of the relationships between intensity changes and both subglottal pressure and air flow rate was undertaken. Figure 5 is a plot of each subject's mean subglottal air pressure as a function of the relative intensity during phonation of the vowels /a/ and /i/. Figure 6 represents this relationship for the conditions with the mouthpiece inserted. Figures 5 and 6 show that there is a positive relationship between subglottal air pressure and relative intensity. The Pearson Product-Moment Correlation Coefficient computed between these two variables was .98.

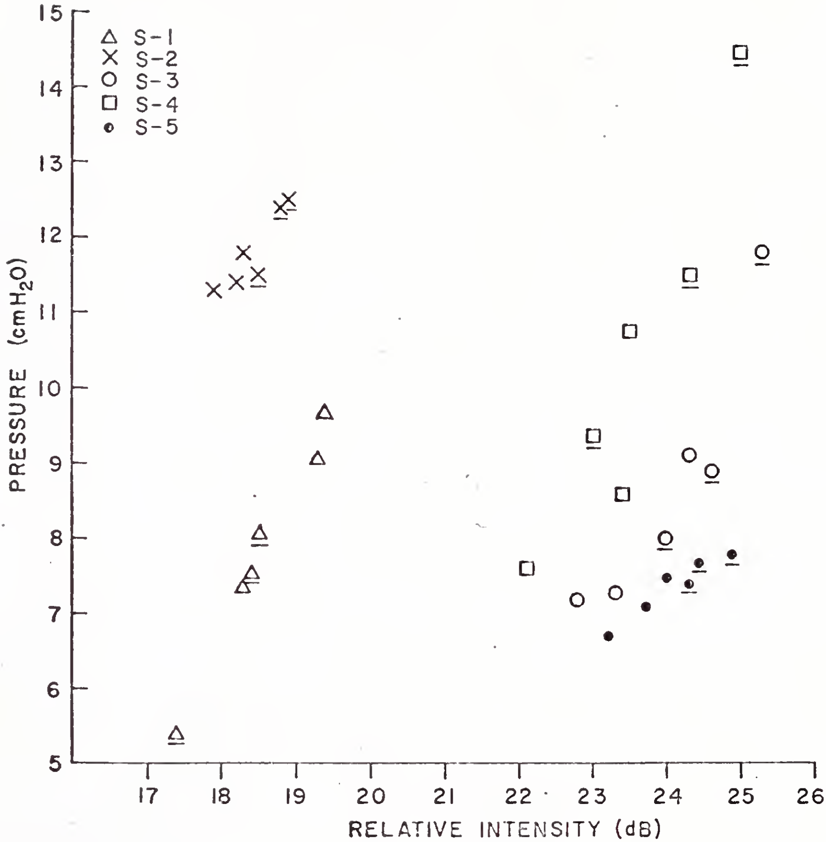

Figure 5. Mean subglottal pressure as a function of the relative intensity for five subjects phonating the vowels /a/ and /i/ in vocal fry. The values for /i/ are underlined.

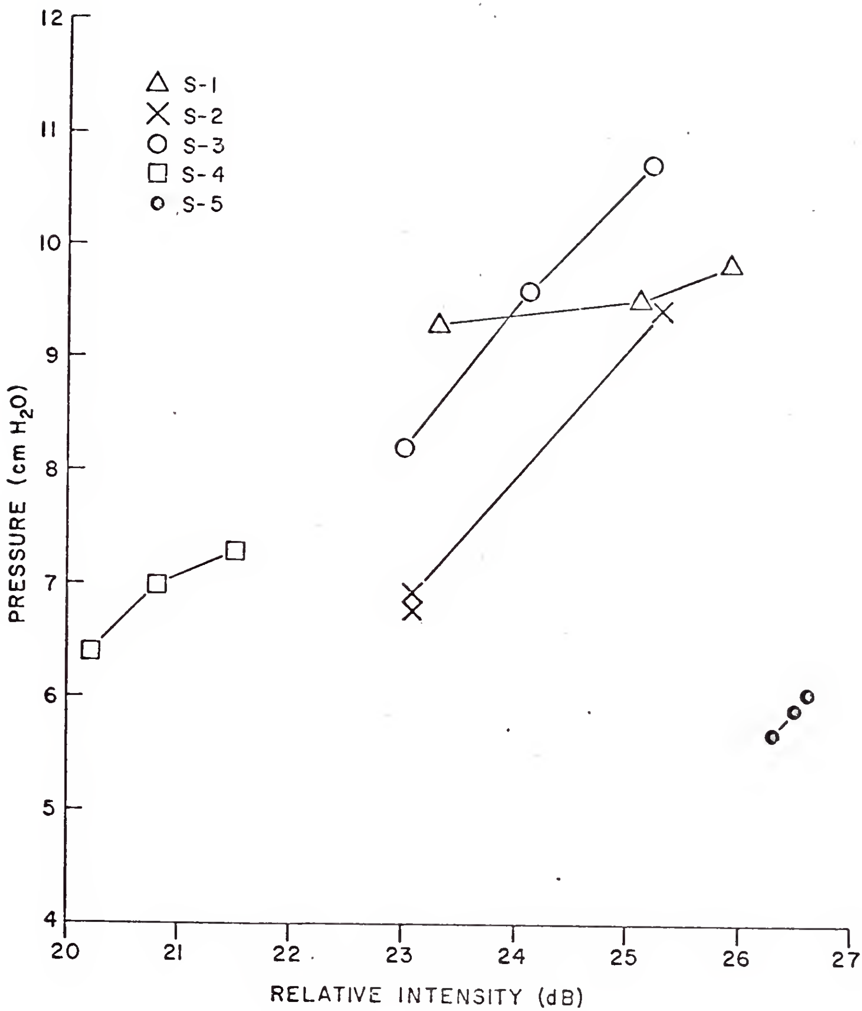

Figure 6. Mean subglottal pressure as a function of the relative intensity for five subjects phonating the vowel /a/ in vocal fry with the mouthpiece in place.

In Figure 7 the mean rate of air flow is plotted as a function of the relative intensity. It can be seen that air flow rate generally increased as a function of the relative intensity and that the rate of increase varied from subject to subject.

For the five subjects used in the present investigation, it may be concluded that subglottal pressure and air flow tend to increase as vocal fry repetition rate increases. In addition, increases in subglottal pressure and to a lesser degree, air flow, produced during vocal fry are related to increases in the relative intensity level of vocal fry phonation.

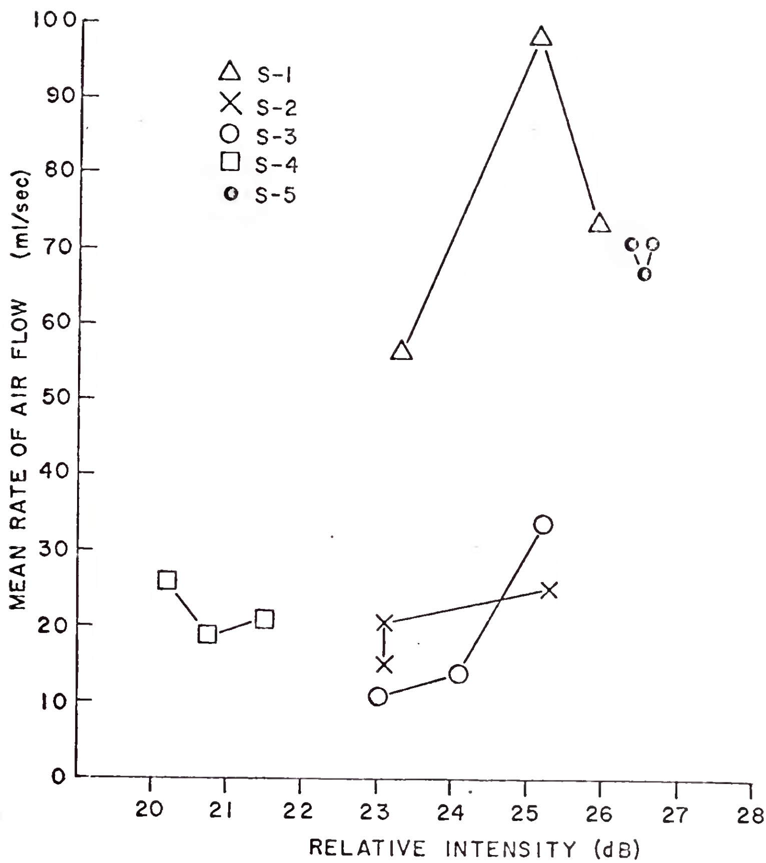

Figure 7. Mean air flow rate as a function of the relative intensity for five subjects phonating the vowel /a/ in vocal fry.

CHAPTER IV

DISCUSSION

The subjects in the present investigation utilized essentially normal laryngeal mechanisms (as determined by the subject-selection criteria) to produce vocal fry and mid-range phonation which were found to be highly dissimilar in terms of the aerodynamic measures accompanying them. The results indicate that both the mean subglottal air pressure and the mean air flow rate during vocal fry are significantly different from those during low frequency modal phonation. The subglottal pressures produced during vocal fry were greater than those recorded in low modal phonation while the mean rate of air flow during fry was less than that for mid-range phonation. Subglottal pressure tended to increase as a function of the repetition rate during vocal fry; it decreased as the subjects went from approximately their 10 percent to their 30 percent mid-range frequencies. Air flow, although highly variable during both types of phonation, tended to decrease slightly as vocal fry repetition rate increased. During modal phonation the mean air flow rates were essentially the same for the two conditions. These results and their relationships to previous studies are discussed in the following paragraphs.

Subglottal Pressure and Type of Phonation

Prior to this study, no measures of subglottal pressure during vocal fry phonation had been reported. Nonetheless the finding of relatively large subglottal pressures departs somewhat from a previous prediction of low pressures during vocal fry (Hollien, Moore, Wendahl, and Michel, 1966). Several factors may be considered to account for the high pressures. First of all, the subglottal pressure may increase as the subject deviates from the region at which he usually phonates. The results of this study and of Kunze's (1962) show that the smallest subglottal pressures are in the region usually used during normal conversation. Kunze found that as a subject deviates either below or above the 30 percent frequency in the modal phonational range, the subglottal pressure tends to increase. In fact he 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 work of Flanagan and Langraf (1967) suggests a possible explanation of the unexpected high pressures found during vocal fry phonation. Using the variables of subglottal pressure, vocal cord tension, and the properties of the contacting surfaces of the folds at closure, Flanagan and Langraf have shown that subglottal pressure is related to the duty cycle of the wave form. Although their model is not specifically related to vocal fry phonation, their calculated values indicate that with a moderate amount of tension and relatively long closed time, the accompanying subglottal pressure is higher than at short closed times and extremely high or low levels of tension. This model is in agreement with earlier work by Van den Berg (1956) who suggested that 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. He also suggests that if the area of the opening is small, air flow rate could be expected to be low. In fry the area of the opening appears to be temporally small with respect to the total period (Coleman, 1968). Therefore, pressure may build during the long closed phase and then force apart the apparently large vocal fold mass.

The high pressures in fry may also be related to the effects of the volume of air in the lungs at the beginning and end of phonation. It has been reported by Draper, Ladefoged, and Whitteridge (1957), by Kunze (1964), and by Perkins and Yanagihara (1968) that pressure is greatest when lung volume is greatest. In the present experiment, subjects produced the fry and mid-range samples directly after inhalation, that is at relatively large lung volumes. The obtained values for air flow clearly indicate that the subject must retain a relatively larger lung volume for a longer period of time in vocal fry than in modal phonation. Consequently, high pressures could be expected during sustained vocal fry phonation when lung volume is relatively large. However, since fry appears to occur normally at the ends of sentences and phrases at relatively low lung volumes, it is not unlikely that it could also be produced with low subglottal pressures. There appears to be a need for additional research concerning lung volume and subglottal pressure during vocal fry. In particular, subglottal pressure should be measured at various lung volumes when the speaker is reported to be phonating in vocal fry.

The subglottal pressures obtained during the modal phonation conditions of this study are in agreement with those obtained by Kunze (1962) although it should be remembered that he used the 10 and 30 percent points of the phonational range including the falsetto frequencies. Therefore, although the actual frequencies at which his subjects were phonating were not reported, it may be assumed that they were phonating at frequencies somewhat higher than the present subjects. Nevertheless, he found a statistically significant drop in pressure amounting to approximately one centimenter of water as the subjects went from their 10 percent frequency to their 30 percent frequency of the modal-falsetto phonational range.

In the present study there was also a significant change in the subglottal pressure between the two points of each subject's range; however, due to the variability both within and between subjects, it can only be said that there was a drop in pressure as the subjects approached their 30 percent modal frequency from their 10 percent modal frequency region.

Air Flow and Type of Phonation

The flow rates found during vocal fry phonation tend to agree with those previously reported by McGlone (1967). Using a respirometer, he obtained flow rates ranging from 2.0 to 71.9 ml/sec. The present results are in general agreement with McGlone's; however, the frequency ranges over which air flow was measured in the two studies are somewhat different. His subjects produced repetition rates ranging from 10.9 to 52.1 pps while the subjects in the present study had a combined range from 39.7 to 90.4 pps. Neither study demonstrated a significant relationship between repetition rate and air flow rate while both showed that flow rate is highly variable between subjects and within consecutive samples from the same subject.

When compared to the flow rates obtained for modal phonation, the fry air flow values are considerably lower. The mid-range flow rates in this study extended from 60.0 to 177.1 ml/sec. While this range overlaps the fry air flow range, there was no overlap for any one subject. In general, the mean air flow rates obtained during modal phonation for the present subjects (107.6 and 121.7 ml/sec for the 10 and 30 percent frequencies respectively) agree with those obtained by Kunze (1962), Isshiki (1964) and by Perkins and Yanagihara (1968).

The flow rates recorded during vocal fry are generally lower than those accompanying falsetto phonation. Isshiki's (1964) lowest reported falsetto air flow rate was 59.4 ml/sec; most of the fry values reported in this study and in McGlone's (1967) are lower. 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 data support the prediction of Hollien, Moore, Wendahl, and Michel (1966).

Effects of Vowels on Modal and Vocal Fry Phonation

The effects of the vowels upon the subglottal pressure during vocal fry appear similar to results obtained for modal range phonation (Ladefoged and McKinney, 1963). That is, during vocal fry the /i/ was consistently associated with greater subglottal air pressure than the /a/. When individual samples of /a/ and /i/ produced by the same subject and having the same relative intensity are compared, the subglottal pressures are greater for phonation of /i/. Ladefoged and McKinney (1963) report that for a given sound pressure level, subglottal pressures produced during sustained phonation of /i/ are greater than those produced during /a/. Thus, as one changes the configuration of the vocal tract from /a/ to /i/, the subglottal pressure is increased; a relationship can be noted for vocal fry phonation also.

Effects of Intensity Changes

Consideration must also be given to the effects of the relative intensity upon the fundamental frequency, subglottal pressure, and air flow rate. Since the intensity and the subglottal pressure varied simultaneously during vocal fry phonation, it would appear that the effect of these two variables on the repetition rate should be considered together. Although the subjects, with the help of the experimeter attempted to control intensity, they appeared to increase intensity as repetition rate increased during the practice and the experimental sessions. Thus, with the present subjects, it was not possible to completely separate the increases in repetition rate and vocal intensity with respect to increases in the subglottal pressure.

Variability Associated with Laryngeal Operation

Although there are certain consistent patterns in the subglottal pressures of vocal fry and modal phonation which have been demonstrated in this and other studies, some individuals appear to vary greatly in both the air pressure and the air flow rate which accompanies phonation. This variability may be the result of individuals exhibiting various patterns of pressure/flow/frequency relationships as suggested by Smith (1954) and Van den Berg (1958). For example, since the lungs are highly elastic, the pressure created by their recoil varies directly with their volume. Thus, while the subjects inhaled prior to phonation, there is no way to ascertain that they had inhaled maximally or that they all began with the same lung volume for each phonation sample. Furthermore, the task was one which demanded sophistication in control of the intrinsic and extrinsic laryngeal musculature. Failure to maintain this high level of control may have resulted in significant changes in phontaion. That such changes occur has been demonstrated by Hollien (1962b), Hollien and Moore (1960) and Damste, Hollien, Moore, and Murry (1968). These authors have shown that within the framework of myoelastic-aerodynamic vocal fold operation, small changes in vocal fold length and thickness may be associated with relatively large changes in the fundamental frequency of phonation. While changes in vocal fold length as a function of the fry repetition rate have not been demonstrated (Hollien, Damste, and Murry, 1969), additional information is needed to understand the relationships among such variables as vocal fold tension, thickness, and repetition rate during vocal fry.

CHAPTER V

SUMMARY AND CONCLUSIONS

The purpose of this investigation was to determine the subglottal pressure and air flow rates which accompany vocal fry phonation. A secondary purpose was to examine the relationships between the repetition rate in vocal fry and the variables of subglottal air pressure and mean rate of air flow. To achieve these purposes, simultaneous measures of the intratracheal air pressure, air flow rate, and sound pressure during vocal fry and modal range phonation were obtained. Recordings were made during sustained phonation of two vowels at three vocal fry and two modal range fundamental frequencies. The subglottal pressure was measured directly through a hypodermic needle inserted between the first and second tracheal rings, air flow was measured through a pneumotachograph inserted into the mouth, the sound pressure was measured with probe tube microphone inserted into the mouthpiece of the pneumotachograph. The voice signal, subglottal pressure, and air flow were recorded simultaneously on an oscillographic writer and FM magnetic tape recorder. The subglottal air pressure and air flow rate recorded on the multritrace oscillographic writer were sampled at 100 ms intervals and converted into numerical values to estimate the actual subglottal air pressure and air flow rate. Fundamental frequency was obtained from wave-to-wave measurements of the voice signal. The data were submitted to statistical analyses in order to test differences in pressure and flow as they relate to fundamental frequency, vowel, and addition of the mouthpiece to the recording apparatus.

From this investigation the following findings were obtained:

1. The rate of air flow produced during vocal fry is less than that produced during modal range phonation. Although flow rate is variable, there is no overlap in the modal and vocal fry frequency ranges for individuals.

2. Air flow rate does not seem related to frequency of phonation in vocal fry or modal range phonation.

3. Subglottal air pressures accompanying vocal fry phonation were found to be greater than those accompanying low frequency modal range phonation.

4. There is a tendency for the subglottal pressure to increase as vocal fry frequency increases.

5. Subglottal pressure decreases as fundamental frequency increases between the 10 and 30 percent frequencies in the modal range.

6. During vocal fry and modal range phonation, the subglottal pressures for /i/ are greater than those for /a/.

7. The addition of experimental apparatus for recording air flow reduces the subglottal pressures during vocal fry and modal range phonation.

8. Increases in subglottal pressure during vocal fry are closely related to increases in relative intensity; however, the rate of increase appears to vary individually.

It appears, therefore, that sustained vocal fry phonation results from a relatively low mean rate of air flow compared to that in modal phonation. This conclusion, which is also supported by data obtained using a respirometer (McGlone, 1967), may relate to the characteristically long closed phase of the vocal fry glottal wave form during which time there is no air flow. It might also be expected that flow rates accompanying vocal fry during any type of phonation would also be relatively low since fry is most often heard after lung volume is reduced, for example, at the ends of sentences.

The subglottal pressures found during sustained vocal fry phonation were relatively high in comparison with the pressures in adjacent low modal range frequencies. However, these pressures were of the same general magnitude as those reported by others (Kunze, 1962; Isshiki, 1964) for phonation at the upper portion of the phonational range. This appears to suggest that as one departs from low frequency modal phonation, glottal resistance increases and there is a need to generate higher pressures to sustain vocal fold vibration. This relationship observed for sustained phonation, however, need not be the case during other types of phonation. For example, vocal fry usually occurs briefly at the ends of sentences having downward inflections when both lung volume and intensity also decrease. Thus, it might be hypothesized that relatively high pressures may not be required to produce vocal fry. Indeed, it might be expected that these subglottal pressures would not differ greatly from those directly preceding them in modal phonation

APPENDIX A

PHONATIONAL RANGES

Table 7. Phonational ranges for the five subjects used in the present investigation. The measures are reported in Hz 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

*it should be noted that these values are higher than those reported in a previous study of vocal fry phonational ranges (Hollien and Michel, 1968). Hoever, during the experimental sessions, only Subjects 3 and 4 produced fundamental frequencies which exceeded previously obtained range limits. These high fundamentals may have resulted from variation from vocal fry to a voice quality containing perceptual elements of both modal and vocal fry. The high frequency vocal fry samples were accepted for analysis since the subjects reported themselves to be phonating in vocal fry and, furthermore, because the pressures associated with these samples were similar to the pressures produced by the subjects at lower fry frequencies and dissimilar to the pressures found for the low frequency modal phonation samples.

APPENDIX B

RECORDING SEQUENCE

Recording sequence followed throughout the experiment

A. Needle inserted; air flow recording apparatus disconnected.

Pressure recordings only

1. Slow fry* /a/
2. Slow fry /i/
3. Medium fry /a/
4. Medium fry /i/
5. Fast fry /a/
6. Fast fry /i/
7. Modal 10% /a/
8. Modal 10% /i/
9. Modal 30% /a/
10. Modal 30% /i/

B. Needle inserted; air flow recording apparatus inserted.

Pressure and flow recordings

1. Slow fry /a/
2. Medium fry /a/
3. Fast fry /a/
4. Modal 10% /a/
5. Modal 30% /a/

*The terms, slow, medium, and fast refer to the reference signals. The samples which the subjects produced were later grouped tc fit these categories.

APPENDIX C

PROCEDURES FOR MEASURING SUBGLOTTAL AIR PRESSURE AND RATE OF AIR FLOW

PROCEDURES FOR MEASURING SUBGLOTTAL AIR PRESSURE AND RATE OF AIR FLOW

Measurement of the subglottal air pressure and rate of air flow were obtained from the analog output of a Multi-trace Oscillographic Writer. The analog output is presented schematically in Figure 8. This figure shows a reference line (set to atmospheric pressure), the subglottal pressure trace (Line A), the air flow trace (Line B), and the vertical time lines placed at 100 ms intervals. To obtain the mean subglottal pressure from this oscillogram, the distance from the Reference Line to Line A was measured at 100 ms intervals. The distance in centimeters at each point was then converted to cm H_2O by multiplying it by the calibration factor. The average of 30 such measures resulted in the mean subglottal air pressure for that particular sample.

The mean rate of air flow was obtained similar to that for the pressure. The distance from the Reference Line to Line B was measured in centimeters at 100 ms intervals and multiplied by the appropriate calibration factor to produce a flow rate in ml/sec.

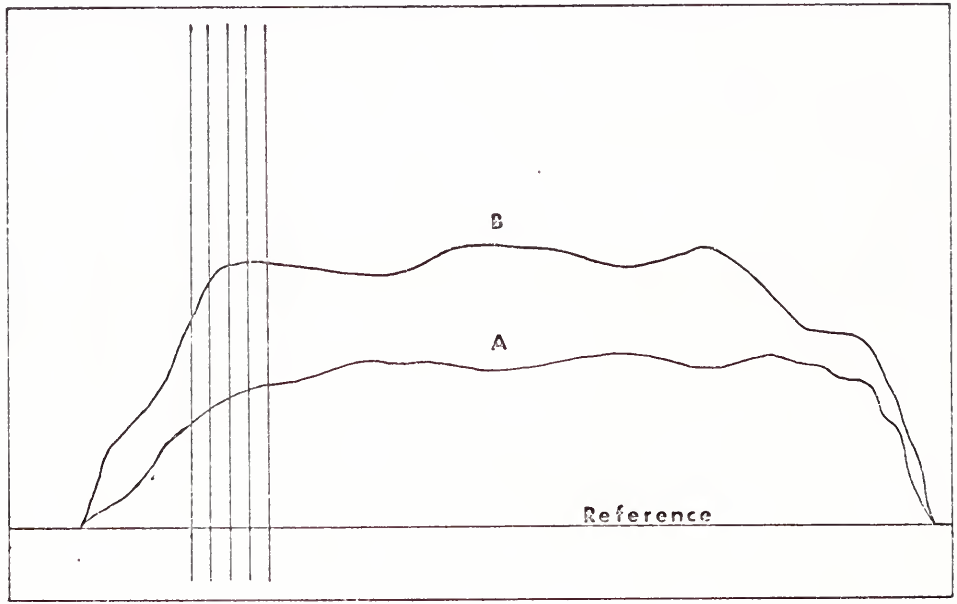

Figure 8. Schematic representation of the output from the Multi-trace Oscillograph used in measuring subglottal pressure and rate of air flow. Line A represents a pressure shift, line B represents an air flow shift. The vertical lines represent time markers.

APPENDIX D

INDIVIDUAL AND COMBINED MEANS OF THE FUNDAMENTAL FREQUENCY, SUBGLOTTAL AIR PRESSURE, RATE OF AIR FLOW, AND RELATIVE INTENSITY FOR PHONATION OF /a/ AND /i/ AT FIVE FREQUENCY REGIONS

Table 8. Mean fundamental frequency, air pressure, rate of air flow, and relative intensity for the vowels /a/ and /i/ at five phonation regions for Subject 1. In conditions 1-10 rate of air flow was not recorded.

Condition	Fundamental Frequency (Hz) $\overline{X}$	Pressure (cm H_2O) $\overline{X}$	Air Flow (ml/sec) $\overline{X}$	Relative Intensity $\overline{X}$ (dB)
1. Slow Fry /a/	48.88	7.35		18.27
2. Slow Fry /i/	48.93	8.03		18.55
3. Medium Fry /a/	50.68	9.73		19.43
4. Medium Fry /i/	50.45	5.38		17.40
5. Fast Fry /a/	64.36	9.04		19.28
6. Fast Fry /i/	53.81	7.47		18.40
7. 10% /a/	84.43	10.80		19.20
8. 10% /i/	92.86	11.08		19.70
9. 30% /a/	115.10	7.53		19.40
10. 30% /i/	98.09	9.03		19.50
11. Slow Fry /a/	42.77	9.26	56.61	23.30
12. Medium Fry /a/	49.24	9.46	98.33	25.10
13. Fast Fry /a/	57.48	9.79	72.71	25.90
14. 10% /a/	72.40	12.48	111.75	26.40
15. 30% /a/	89.68	10.61	111.26	26.20

Table 9. Mean fundamental frequency, air pressure, rate of air flow, and relative intensity for the vowels /a/ and /i/ at five phonation regions for Subject 2. In conditions 1-10 rate of air flow was not recorded.

Condition	Fundamental Frequency (Hz) $\overline{X}$	Pressure (cm H_2O) $\overline{X}$	Air Flow (ml/sec) $\overline{X}$	Relative Intensity $\overline{X}$
1. Slow Fry /a/	43.55	11.53		18.50
2. Slow Fry /i/	40.36	11.46		18.13
3. Medium Fry /a/	48.45	11.28		17.96
4. Medium Fry /i/	48.37	12.52		18.83
5. Fast Fry /a/	54.49	11.88		18.30
6. Fast Fry /i/	62.27	12.46		18.67
7. 10% /a/	78.85	5.16		19.50
8. 10% /i/	79.38	5.30		19.80
9. 30% /a/	90.65	5.95		19.70
10. 30% /i/	105.47	5.02		20.10
11. Slow Fry /a/	41.84	6.86	20.59	23.13
12. Medium Fry /a/	51.03	6.93	15.52	23.13
13. Fast Fry /a/	73.48	9.45	25.38	25.27
14. 10% /a/	86.58	5.21	87.35	26.40
15. 30% /a/	116.87	4.76	170.80	26.30

Table 1.0. Mean fundamental frequency, air pressure, rate of air flow, and relative intensity for the vowels /a/ and /i/ at five phonation regions for Subject 3. In conditions 1-10 rate of air flow was not recorded.

Condition	Fundamental Frequency (Hz) $\overline{X}$	Pressure (cm H_2O) $\overline{X}$	Air Flow (ml/sec) $\overline{X}$	Relative Intensity $\overline{X}$
1. Slow Fry /a/	46.51	7.22		22.77
2. Slow Fry /i/	46.63	8.00		24.00
3. Medium Fry /a/	56.63	7.25		23.27
4. Medium Fry /i/	51.46	8.88		24.60
5. Fast Fry /a/	88.41	9.16		24.30
6. Fast Fry /i/	77.21	11.79		25.33
7. 10% /a/	98.09	6.52		25.00
8. 10% /i/	102.76	6.53		24.90
9. 30% /a/	137.40	4.85		25.30
10. 30% /i/	139.00	5.84		25.30
11. Slow Fry /a/	53.38	9.66	13.79	24.10
12. Medium Fry /a/	58.54	8.17	11.57	23.07
13. Fast Fry /a/	85.50	10.68	35.38	25.17
14. 10% /a/	102.82	4.13	101.75	26.40
15. 30% /a/	138.40	3.48	67.59	26.60

Table 11. Mean fundamental frequency, air pressure, rate of air flow, and relative intensity for the vowels /a/ and /i/ at five phonation regions for Subject 4. In conditions 1-10 rate of air flow was not recorded.

Condition		Fundamental Frequency (Hz) $\overline{X}$	Pressure (cm H_2O) $\overline{X}$	Air Flow (ml/sec) $\overline{X}$	Relative Intensity $\overline{X}$
1.	Slow Fry /a/	45.23	7.67		22.13
2.	Slow Fry /i/	45.27	9.41		23.00
3.	Medium Fry /a/	52.86	8.60		23.37
4.	Medium Fry /i/	52.99	10.82		23.53
5.	Fast Fry /a/	66.25	11.52		24.33
6.	Fast Fry /i/	90.39	14.50		25.00
7.	10% /a/	103.89	7.39		24.90
8.	10% /i/	109.14	6.85		25.30
9.	30% /a/	136.52	5.68		25.40
10.	30% /i/	124.51	8.61		25.60
11.	Slow Fry /a/	49.56	7.26	21.20	21.53
12.	Medium Fry /a/	60.59	6.47	26.60	20.20
13.	Fast Fry /a/	78.88	7.05	19.62	20.73
14.	10% /a/	114.69	2.61	60.02	23.70
15.	30% /a/	133.67	3.65	141.62	24.00

Table 12. Mean fundamental frequency, air pressure, rate of air flow, and relative intensity for the vowels /a/ and /i/ at five phonation regions for Subject 5. In conditions 1-10 rate of air flow was not recorded.

Condition		Fundamental Frequency (Hz) $\overline{X}$	Pressure (cm H_2O) $\overline{X}$	Air Flow (ml/sec) $\overline{X}$	Relative Intensity $\overline{X}$
1.	Slow Fry /a/	41.06	7.11		23.76
2.	Slow Fry /i/	39.74	7.70		24.43
3.	Medium Fry /a/	46.03	7.49		24.06
4.	Medium Fry /i/	50.40	7.78		24.90
5.	Fast Fry /a/	56.22	6.70		23.20
6.	Fast Fry /i/	56.74	7.42		24.26
7.	10% /a/	71.84	3.91		24.80
8.	10% /i/	79.79	4.34		25.30
9.	30% /a/	87.81	2.57		25.40
10.	30% /i/	102.76	2.50		25.30
11.	Slow Fry /a/	43.15	6.16	71.00	26.60
12.	Medium Fry /a/	50.51	5.75	71.25	26.37
13.	Fast Fry /a/	59.17	6.10	67.10	26.56
14.	10% /a/	87.79	4.73	177.14	27.20
15.	30% /a/	105.82	3.31	116.88	27.40

Table 13. Mean fundamental frequency, subglottal pressure, and rate of air flow at five phonation conditions for five subjects producing /a/ and /i/.*

Condition	Fundamental Frequency (Hz) $\overline{X}$	Pressure (cmH_2O) $\overline{X}$	Air Flow (ml/sec) $\overline{X}$
1. Slow Fry /a/	44.65	8.18	
2. Slow Fry /i/	44.19	8.92	
3. Medium Fry /a/	50.93	8.87	
4. Medium Fry /i/	50.73	9.08	
5. Fast Fry /a/	65.95	9.66	
6. Fast Fry /i/	68.08	10.73	
7. 10% /a/	87.42	6.84	
8. 10% /i/	92.78	6.82	
9. 30% /a/	113.50	5.32	
10. 30% /i/	113.97	6.20	
11. Slow Fry /a/	46.14	7.84	36.64
12. Medium Fry /a/	53.98	7.36	44.65
13. Fast Fry /a/	70.90	8.62	44.04
14. 10% /a/	92.86	5.63	107.60
15. 30% /a/	116.89	4.46	121.65

*Since there was no way of assuring that each subject was situated at exactly the same distance from the microphone, the relative intensity measures were not averaged.

BIBLIOGRAPHY

Brackett, I., An analysis of the vibratory action of the vocal folds during the production of tones at selected frequencies. Ph.D. dissertation, Northwestern University, 1947.

Coleman, R., Decay characteristics of vocal fry, Folia Phoniatrica, 15, 256-263 (1963).

Coleman, R., Pulse patterns of vocal fry, Paper presented at Forty-Fourth Annual Convention of the American Speech and Hearing Association, Denver, 1968.

Damste, H., Hollien,. H., Moore, P., and Murry, T., An x-ray study of vocal fold length, Folia Phoniatrica, in press (1968).

Draper, M., Ladefoged, p., and Whitteridge, D., Expiratory muscles involved in speech, Journal of Physiology, 138, 17p-18p (1957).

Draper, M., Ladefoged, P., and Whitteridge, D., Respiratory muscles in speech, Journal of Speech and Hearing Research, 2, 16-27 (1959).

Fant, G., Personal communication to H. Hollien and R. Wendahl (1964), in Journal of Acoustical Society of America, 43, 509 (1968).

Flanagan, J., and Langraf, L., Self-oscillating source for vocal-tract synthesizers, Preprints of 1967 Conference on Speech Communication and Processing, 54-62 (1967).

Fry, D., Stead, W., Ebert, R., Lubin, R., and Wells, H., The measurement of the intraesophageal pressure and its relationship to intrathoracic pressure, Journal of Laboratory and Clincical Medicine, 40, 664-673 (1952).

Hardy, J., Air flow and air pressure studies, American Speech and Hearing Association Reports, 1, 141-152 (1965).

Hays, W. L., Statistics for Psychologists, New York: Holt, Rinehart, and Winston, Inc. (1963).

Hollien, H., Personal communication, December, 1968.

Hollien, H., Vocal pitch variation related to changes in vocal fold length, Journal of Speech and Hearing Research, 3, 150-156 (1960).

Hollien, H., The relationship of vocal fold length to vocal pitch for female subjects, Proceedings of the XII International Congress of Logopedics and Phoniatrics, Scoula Tipografica dell'Ente Nationale Sordomuti, Padua, 38-43 (1962).

Hollien, H., The relationship of vocal fold thickness to absolute fundamental frequency of phonation, Proceedings of the Fourth International Congress of Phonetic Sciences, The Hague: Mouton and Company, 173-177 (1962a).

Hollien, H., Vocal fold thickness and fundamental frequency of phonation, Journal of Speech and Hearing Research, 5, 237-243 (1962b).

Hollien, H., Coleman, R., and Moore, P., Stroboscopic laminagraphy of the larynx during phonation, Acta Oto-laryngologica, 65, 209-215 (1968).

Hollien, H., and Curtis, J., A laminagraphic study of vocal pitch, Journal of Speech and Hearing Research, 3, 361-371 (1960).

Hollien, H., Damste, H., and Murry, T., Vocal fold length during vocal fry phonation, in press, Folia Phoniatrica, 1969.

Hollien, H., and Michel, J., Vocal fry as a phonational register, Journal of Speech and Hearing Research, 11, 600-604 (1968).

Hollien, H., and Moore, P., Measurements of the vocal folds during changes in pitch, Journal of Speech and Hearing Research, 3, 157-165 (1960).

Hollien, H., Moore, P., Wendahl, R., and Michel, J., On the nature of vocal fry, Journal of Speech and Hearing Research, 9, 245-247 (1966).

Hollien, H., and Wendahl, R., Perceptual study of vocal fry, Journal of the Acoustical Society of America, 43, 506-509 (1968).

Hubbs, J., The new pulse, Journal of the Precision Measurements Association, 39, 109-116 (1966).

Isshiki, N., Regulatory mechanism of the pitch and volume of the voice, Fibi Inkoka Rinsho Kyoto, 52, 1065-1094 (1959).

Isshiki, N., Regulatory mechanism of voice intensity variation, Journal of Speech and Hearing Research, 7, 17-29 (1964).

Irwin, J., A study of the relationships between certain laryngeal mechanisms and vocal pitch. M.A. thesis, The Ohio State University, 1940.

Kunze, L., An investigation of the changes in subglottal pressure and rate of air flow accompanying changes in fundamental frequency, intensity, and vowels and voice registers in male speakers, Ph.D. dissertation, State University of Iowa, 1962.

Kunze, L., Evaluation of methods of estimating subglottal air pressure, Journal of Speech and Hearing Research, 7, 151-163 (1964).

Ladefoged, P., Subglottal activity during speech, Proceedings of the Fourth International Congress of Phonetic Sciences, The Hague: Mouton and Company, 73-91 (1962).

Ladefoged, P., Draper, M., and Whitteridge, D., Syllables and stress, Miscellanea Phonetica, 3, 1-14 (1958).

Ladefoged, P., and McKinney, N., Loudness, sound pressure, and subglottal pressure in speech, Journal of the Acoustical Society of America, 35, 454-460 (1963).

Lindquist, E. F., Design and Analysis of Experiments in Psychology and Education, Boston: Houghton-Mifflin Co. (1953).

Lieberman, P., Direct comparison of subglottal and esophageal pressure during speech, Journal of the Acoustical Society of America, 43, 1157-1165 (1968).

McGlone, R., Air flow during vocal fry, Journal of Speech and Hearing Research, 10, 299-304 (1967).

Mead, J., and Whittenberger, J., Physical properties of the human lungs measured during spontaneous respiration, Journal of Applied Physiology, 5, 779-796 (1953).

Michel, J., and Hollien, H., Perceptual differentiation of vocal fry and harshness, Journal of Speech and Hearing Research, 11, 439-443 (1968).

Moore, P., and Von Leden, H., Dynamic variations of the vibratory pattern in the normal larynx, Folia Phoniatrica, 10, 205-238 (1958).

Morner, J., Franeson, P., and Fant, G., Voice register terminology and standard pitch, Speech Transmission Laboratory Quarterly Progress Report, No. 4 (1963).

Perkins, W., and Yanagihara, N., Parameters of voice production 1. Some mechanisms for the regulation of pitch, Journal of Speech and Hearing Research, 11, 246-268 (1968).

Rossier, P., Buhlmann, A., and Wiesinger, K., Respiration Physiology Principles and Their Clinical Applications, translated by P. Luschinger and K. Moser, St. Louis: C. V. Mosby Co. (1954).

Smith, S., Remarks on the physiology of the vibrations of the vocal cords, Folia Phoniatrica, 6, 166-178 (1954).

Sonninen, A., Is the length of the vocal cords the same at all different levels of singing? Acta-Otolaryngologica, Supplement 118, 219-231 (1954).

Sonninen, A., The role of the external laryngeal muscles in length adjustment of the vocal cords in singing, Acta-Otolaryngologica, Supplement 130, 102 (1956).

Timke, R., Von Leden, H., and Moore, P., Laryngeal Vibrations: measurements of the glottic wave, Part 2, Physiologic variations, Archives Otolaryngologica, 68, 438-444 (1958).

Van den Berg, J., Direct and indirect determination of the mean subglottal pressure, Folia Phoniatrica, 8, 1-24 (1956).

Van den Berg, J., Myoelastic-aerodynamic theory of voice production, Journal of Speech and Hearing Research, 1, 227-240 (1958).

Van den Berg, J., Physiology and physics of voice production, Acta-Physiologica et Pharmacologica Neerlandica, 5, 40-55 (1956).

Wendahl, R., Moore, P., and Hollien, H., Comments on vocal fry, Folia Phoniatrica, 15, 251-255 (1963).

Wendler, Von, Zur messung der stimmlippenlange, Zeipschlift fur Laryngologie, Rhinologie, Otologie und Ihre Grenzgebiepe, 44, 162-173 (1964).

Winer, B. J., Statistical Principles in Experimental Design, New York: McGraw-Hill Book Co. (1962).

BIOGRAPHICAL SKETCH

Thomas Murry was born September 10, 1943, at Sewickley, Pennsylvania. In June, 1961, he was graduated from Ambridge Senior High School, Ambridge, Pennsylvania. He received a Bachelor of Science degree with a major in Speech Pathology in May, 1964, from Indiana University of Pennsylvania. In September, 1964, he enrolled in the Graduate School of The Ohio State University where he was a recipient of a Neurological and Sensory Disease Fellowship. In May, 1965, he was graduated from The Ohio State University with a Master of Arts degree with a major in Voice Science. He enrolled in the Graduate School of the University of Florida in September, 1966. He held a research assistantship there until September, 1968, followed by a faculty appointment as Interim Instructor until December, 1968.

This dissertation was prepared under the direction of the candidate's supervisory committee and has been approved by all members of that committee. It was submitted to the Dean of the College of Arts and Sciences and to the Graduate Council, and was approved as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

March 25, 1969

Dean, College of Arts and Sciences

Dean, Graduate School

Supervisory Committee:

Chairman