Determination of the Rate of Change of Fundamental Frequency with Respect to Subglottal Air Pressure During Sustained Phonation

PHILIP LIEBERMAN

Haskins Laboratories, New York, New York 10017

and

The University of Connecticut, Storrs, Connecticut 06208

RONALD KNUDSON AND JERE MEAD

Physiology Department, Harvard School of Public Health, Boston, Massachusetts 02115

The rate of change of fundamental frequency with respect to transglottal air pressure was determined for a single male speaker by sinusoidally varying buccal air pressure while the speaker sustained short episodes of phonation at various fundamental frequencies. The speaker phonated at two levels of "effort," i.e., "soft" and "loud" phonation with and without auditory feedback. The senstivity of the larynx to variations in transglottal air pressure varied from 3 to 18 Hz/cm H_2O. Fundamental frequency was most sensitive to variations in transglottal air pressure at high frequencies and in the "soft" mode of phonation. The minimum transglottal air pressure for sustained phonation was 2–3 cm H_2O. These results are consistent with some earlier studies and a recent theoretical model of laryngeal activity. These results further indicate that variations in subglottal air pressure and adjustments in laryngeal muscular tension both play a role in regulating fundamental frequency during normal speech.

The physiological factors and articulatory maneuvers that determine the acoustic output of the larynx have been known qualitatively since Johannes Muller's classic experiments in the early part of the nineteenth century. Muller found in these experiments[1] with excised human larynges that the fundamental frequency of phonation was a function of both the tension of the vocal cords and the subglottal air pressure. A number of investigators have since obtained data on the relationship between the fundamental frequency of phonation and subglottal air pressure. These data suggest that this relationship may vary with different fundamental frequency ranges and manners of phonation. Van den

Berg,[2] in experiments with excised human larynges, has found that the rate of change of f_0 with respect to subglottal air pressure, $\Delta f_0/\Delta P$, ranges from 2.5 to 20 Hz/cm H_2O for the same larynx. Ohman and Lindqvist[3] and Ladefoged[4] measured $\Delta f_0/\Delta P$ while normal male speakers sang sustained notes, and obtained values of 2.5 and 5 Hz/cm H_2O, respectively. Lieberman,[5] in an experiment with normal male speakers, used an indirect technique in which f_0 was correlated with subglottal air pressure at points where laryngeal tension was assumed to be constant. During the production of

* The experimental data for this experiment were obtained while this author was attached to the Speech Research Branch of the Air Force Cambridge Res. Labs., Bedford, Mass.
[1] J. Muller, "Von der Stimme und Sprache," *Handbuch der Physiologia des Menschen*, (J. Holscher, Coblenz, Germany, 1837), Vol. 2, Book 4, Part 3, pp. 133–245.

[2] J. Van den Berg, "Direct and Indirect Determination of the Mean Subglottal Pressure," Folia Phoniat. 8, 1–24 (1956).
[3] S. Öhman and J. Lindqvist, "Analysis and Synthesis of Prosodic Pitch Contours," Quart. Progr. Status Rep. Speech Transmission Lab., Roy. Inst. Technol., Stockholm, 1965.
[4] P. Ladefoged, "Subglottal Activity During Speech," Proc. Fourth Intern. Congr. Phonetic Sci., 4th, 247–265 (1962).
[5] P. Lieberman, *Intonation, Perception and Language* (MIT Press, Cambridge, Mass., 1967).

English sentences, $\Delta f_0/\Delta P$ ranged from 16 to 21 Hz/cm H_2O.

The object of this experiment is to determine, for a single speaker singing sustained notes, the range over which $\Delta f_0/\Delta P$ varies. The speaker therefore sang at different average fundamental frequencies at different degrees of vocal effort, with and without auditory feedback.

I. PROCEDURE

A normal male speaker (J.M.) assumed an erect sitting position in a volume plethysmograph. The speaker had participated in the earlier study reported by Lieberman.[5] (His utterances are labeled *Speaker 3* in that study.) The speaker's head was outside the plethysmograph, which was sealed at his neck by a rubber collar in the manner described by Bouhuys, Proctor, and Mead.[6] Subglottal air pressure was measured with an esophageal balloon, following the technique noted by Bouhuys, Proctor, and Mead.[6] This technique yields accurate measures of subglottal air pressure during speech.[7] A contact microphone adapted from an Altec type 633 A microphone[8] was placed against the speaker's trachea just above the clavicle. A rigid, 32-mm-o.d. plastic tube was supported at the level of the speaker's mouth. This tube led into a rigid box. An Acoustic Research AR-1 low-frequency loudspeaker was mounted facing into this box. The loudspeaker was excited by a solid-state power amplifier that in turn was controlled by an oscillator. It was thus possible to vary the air pressure inside this box over a range of ±5 cm H_2O at frequencies down to 2 Hz. This procedure is described in detail by Grimby *et al.*[9] Throughout the series of experiments that are described, the speaker grasped the tube in his mouth while he phonated.

The air-pressure drop across the speaker's glottis is equal to subglottal air pressure minus buccal pressure. When the speaker phonated with the tube in his mouth, the buccal air pressure varied sinusoidally whenever the AR loudspeaker was excited. It was thus possible to observe the effects of sinusoidal variations in transglottal air pressure on the fundamental frequency of phonation. The air pressure in the mouth tube was monitored throughout the experiment with a Sanborn 268 B transducer similar to the one connected to the esophageal balloon. The signals from these transducers and the throat microphone were monitored on a direct writing oscillograph (Sanborn Poly-Viso) and on a two channel

[6] A. Bouhuys, D. F. Proctor, and J. Mead, "Kinetic Aspects of Singing," J. Appl. Physiol. 21, 483–496 (1966).
[7] P. Lieberman, "Direct Comparison of Subglottal and Esophageal Pressure during Speech," J. Acoust. Soc. Amer., 43, 1157–1164, 1968.
[8] H. C. Porter, "Extraction of Pitch from the Trachea," Tech. Rep. AFCRL-63-24, Air Force Cambridge Res. Lab., Bedford, Mass., 1963.
[9] G. Grimby, T. Takishima, W. Graham, P. Macklem, and J. Mead, "Frequency Dependence of Flow Resistance in Patients with Obstructive Lung Disease," J. Clin. Investigation 47, 1455–1465 (1968).
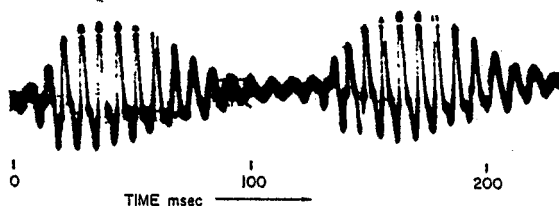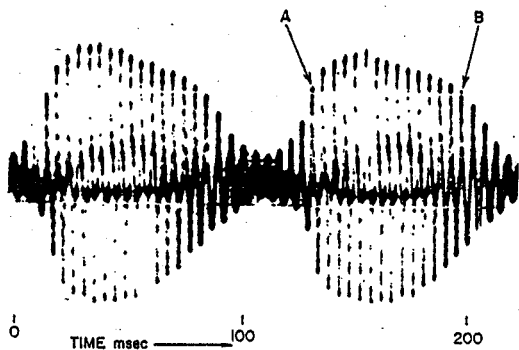
FIG. 1. Oscillogram of phonation at "soft" level of effort. The average fundamental frequency is 139 Hz. Variations in transglottal air pressure of 2.8 cm H_2O were produced at a rate of 8 Hz. Both the amplitude and fundamental frequency of phonation vary at a rate of 8 Hz.

oscilloscope. All the signals were recorded on a multi-channel instrumentation recorder (Precision Instrument model PS 207A) at a tape speed of 7.5 in./sec. The air-pressure signals were recorded on FM channels, while the acoustic signal from the throat microphone was recorded on a direct record channel. Calibrating signals corresponding to known air pressures were recorded at regular intervals, and the gain of the audio channel was frequently monitored on the oscilloscope to minimize waveform distortion.

The experiment was performed in two sessions over a period of three months. The speaker in both sessions produced sustained sounds (approximately 10 sec) at different average fundamental frequencies. In each session, he frequently practiced holding a steady pitch at about 110 Hz, 160 Hz, 220 Hz, and a very high falsetto at 375–500 Hz with the AR loudspeaker turned off. The speaker's fundamental frequency varied less than 5 Hz during the production of these utterances.

The loudspeaker that generated the sinusoidal buccal air-pressure variations was driven at 2, 5, 7, 10, 15, and 20 Hz. The intensity of the buccal air pressure variations ranged from 2 to 6 cm H_2O peak-to-peak. In most cases, the variation in buccal air pressure was maintained at 4 cm H_2O peak-to-peak. The transglottal air pressure thus varied sinusoidally at rates between 2 and 20 Hz at over a range of 2 to 6 cm H_2O. The bandwidth of the subglottal pressure monitoring system was limited to 100 Hz.

II. OBSERVATIONS

In the first session, the speaker phonated at each f_0 level at each rate of transglottal air-pressure variation at two degrees of effort. The speaker phonated at both a "soft" and a "loud" level. In Fig. 1, an oscillogram of "soft" phonation at an average f_0 of 139 Hz is presented. The loudspeaker produced transglottal pressure variations of 2.8 cm H_2O at 8 Hz. Both the amplitude and the fundamental frequency of phonation vary at a rate of 8 Hz. As the transglottal air pressure decreased, so did the amplitude and the fundamental frequency of phonation. The sinusoidal variations in the buccal air pressure in effect modulated the output of the larynx. In this example, the transglottal air pressure varied between 3.5 and 6.3 cm H_2O. Over a transglottal pressure range of 2.5 cm H_2O, the fundamental frequency

FIG. 2. Oscillogram of phonation at "soft" level of effort at an average f_0 of 204 Hz. Note the asymmetry in the envelope of the laryngeal output. A greater transglottal air pressure is necessary to produce the same amplitude during the "buildup" portion of each modulation period. The transglottal air pressure was 5.25 cm H_2O at Point A and 4 cm H_2O at Point B.

FIG. 3. Rate of change of fundamental frequency versus average fundamental frequency for episodes of phonation at "soft" level of effort.

varied from 127 to 152 Hz. The rate of change of f_0 with respect to air pressure was thus equal to 10 Hz/cm H_2O. Fundamental frequency was always measured by measuring and averaging the durations of two adjacent fundamental periods since the durations of adjacent periods were generally different. Pitch perturbations generally occurred[10]; long and short periods characteristically alternated. Note the asymmetry in the envelope of the acoustic signal. Note, also, that the amplitude of phonation is greater at the end of each "cycle" of the "modulated" laryngeal output signal.
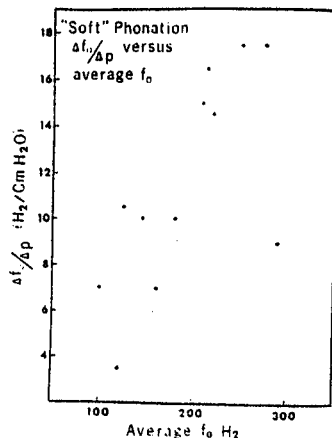
In Fig. 2, this asymmetry in the envelope of the laryngeal output is more apparent. A greater transglottal air pressure is necessary to produce the same envelope amplitude during the "buildup" portion of each modulation period than is the case for the "decay" portion of each modulation period. A transglottal pressure of 5.25 cm H_2O occurred, for example, at Point A. The pressure at Point B was 4 cm H_2O. A greater transglottal air pressure was, in other words, necessary to initiate a given amplitude of phonation than to sustain phonation at that level. The average fundamental frequency in this example is 204 Hz. The transglottal air pressure varied between 3.5 and 6.0 cm H_2O, and f_0 varied between 185 and 223 Hz. The rate of change of f_0 thus was equal to 15 Hz/cm H_2O.

The minimum transglottal air pressure necessary to sustain phonation ranged from 2.2 to 3.0 cm H_2O. Van den Berg and Tan[11] in experiments with excised human larynges found that the minimum transglottal pressure necessary to sustain phonation ranged from 2 to 3 cm H_2O. The minimum transglottal air pressure that was necessary to initiate phonation was 1 to 2 cm greater than the minimum pressure that was necessary

to sustain phonation. It was not possible to correlate higher minimum air pressures with either the average fundamental frequency of phonation or the frequency at which the loudspeaker varied the transglottal air pressure.

The rate of change of fundamental frequency with respect to air pressure was determined for each episode of "soft" phonation with the exception of the utterances where the loudspeaker's frequency was 20 Hz. The measurements of the durations of the fundamental periods was too uncertain when the buccal air pressure varied at this rate (too few fundamental periods occurred in each modulation period). The rate of change of f_0 with air respect to air pressure versus the average fundamental frequency of phonation is presented in Fig. 3. The rate at which the buccal air pressure varied had no apparent effect on the rate of change of f_0. The average transglottal air pressure for these stimuli ranged from 5 to 8 cm H_2O. The highest sustained falsetto that the speaker could produce was approximately 550 Hz, so the upper range of fundamental frequencies plotted in Fig. 3 by no means represents the highest f_0 range of the speaker. Speaker J. M., during the production of nonemotional test sentences in an earlier study, produced fundamental frequencies that ranged from about 60 to 260 Hz, although he generally stayed within the range of 100 to 200 Hz.[5]
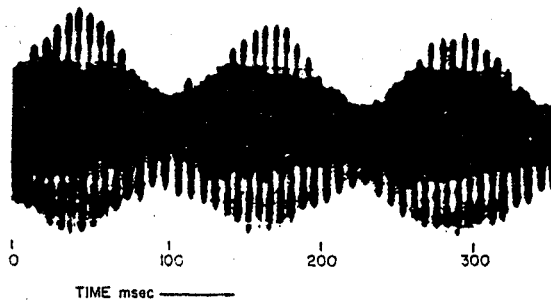

FIG. 4. Oscillogram of phonation at "loud" level of effort. The average f_0 is 132 Hz. The transglottal air pressure was modulated at a rate of 8 Hz.

[10] P. Lieberman, "Perturbations in Vocal Pitch," J. Acoust. Soc. Amer. 33, 597–603 (1961).

[11] J. Van den Berg and T. S. Tan, "Results of Experiments with Human Larynxes," Pract. Oto-Rhino-Laryngol., 21, 425–450 (1959).
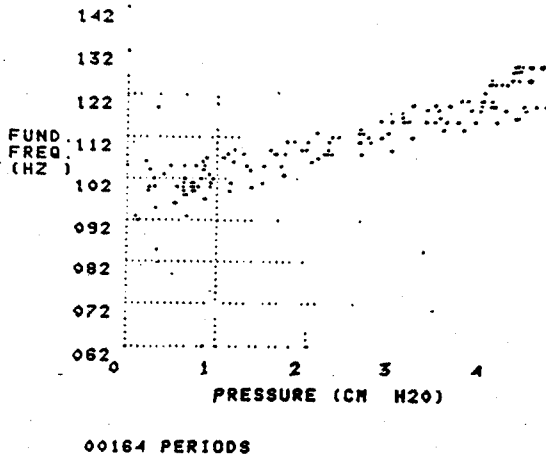
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FIG. 5. Photograph of computer output display. The computer program determined the "instantaneous" fundamental frequency of each fundamental period and plotted it with respect to the differential transglottal air pressure for each episode of "loud" phonation. The number of fundamental periods plotted is also displayed (164 periods). Note that the rate of change of f_0 with respect to air pressure is approximately 7 Hz/cm H_2O.

In Fig. 4, an oscillogram typical of "loud" phonation is presented. The average fundamental frequency for this utterance is 132 Hz, and the buccal air pressure varied at a rate of 8 Hz. A computer program was devised that made use of the Digital Equipment Corportion PDP-1 computer at the Air Force Cambridge Research Laboratories, to measure the fundamental frequency of phonation on a period-by-period basis and to correlate the "instantaneous" fundamental frequency of each individual period with the average transglottal air pressure that occurred during that period. The computer, in other words, measured the duration of each period, computed the reciprocal of the duration (the "instantaneous" fundamental frequency), measured the average transglottal air pressure

during that period, and correlated the fundamental frequency with the transglottal air pressure. The computer program then determined the dc component of the transglottal air pressure and produced a display on the PDP-1 precision oscilloscope output in which the fundamental frequency of each period was plotted with respect to the ac component of the transglottal air pressure.

In Fig. 5, one of these computer output displays is presented. Fundamental frequency is plotted on the ordinate. The differential transglottal air pressure is plotted on the abcissa. The number of fundamental periods plotted in this Figure also was displayed on the computer oscilloscope output. Note that for the 164 periods plotted an increase of 3 cm H_2O is associated with an f_0 rise of approximately 20 Hz. The rate of change of f_0 with respect to air pressure is thus about 7 Hz/cm H_2O. In Fig. 6, a similar plot is presented for an utterance that had a higher average fundamental frequency. The rate of change of f_0 is about 10 Hz/cm H_2O for this sample.

Similar computer derived plots were made for all the "loud" utterances that were recorded in both the first and the second recording sessions. The computer accepted a two second segment of speech for each plot. The middle portion of each episode of phonation was therefore sampled. In Fig. 7, a cumulative distribution is presented for the utterances that had average fundamental frequencies that were close to 110, 150, and 220 Hz. The average fundamental frequencies of individual episodes of phonation actually deviated from these fundamental frequencies by as much as 20 Hz. The data were, however, pooled into these three ranges, which roughly corresponded to three "steps" that the speaker attempted to produce. The average transglottal air pressure for these utterances ranged from 9 to 12 cm H_2O. Note that the rate of change of f_0 with respect to air pressure ranged from 3 to 16.5 Hz/cm H_2O. For phonation at average fundamental frequencies of 110 Hz, the rate of change of f_0 was less than or equal to 5 Hz/cm H_2O 40% of the time. In contrast, for phona-
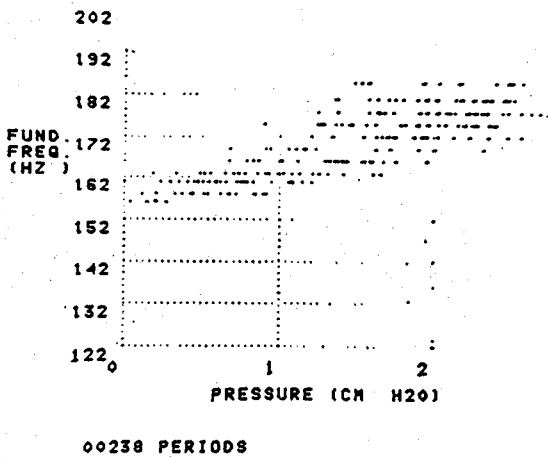

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FIG. 6. Photograph of computer output display for an utterance that had a higher average fundamental frequency. Note that the rate of change of f_0 with respect to air pressure is approximately 10 Hz/cm H_2O.
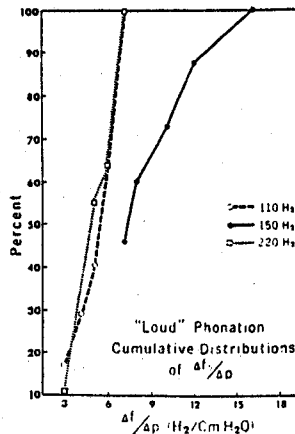

FIG. 7. Cumulative distributions of rate of change of f_0 with respect to air pressure for "loud" utterances that had average fundamental frequencies that were close to 110, 150, and 220 Hz.

tion at an average f_0 of 150 Hz. the rate of change of f_0 was greater than 8 Hz/cm H_2O 40% of the time. The plot for phonation at an average f_0 of 220 Hz is similar to that for phonation at 110 Hz except that the greater rates of change of f_0 occurred more often. Approximately 6000 pitch periods make up the sample size plotted on Fig. 7. These periods were sampled from approximately 800 sec of phonation.

The rate of change of buccal air pressure had no apparent influence on the rate of change of f_0 with respect to air pressure. In the second recording session. half of the utterances were made while the speaker's hearing was masked by means of low-frequency noise. Telephonics TDR 8 microphones were excited by low-pass-filtered random noise (a filter with a slope of 12 dB/oct above 1 kHz was used) so that the speaker was not able to hear his own voice. The only apparent effect of the masking was that the speaker sometimes phonated at an average fundamental frequency that was 5 to 10 Hz higher than he might have in the absence of masking. The rate of change of f_0 with respect to air pressure did not seem to depend on whether the speaker was able to hear his own voice or not. The episodes of phonation that occurred with masking are therefore pooled with the unmasked utterances in Fig. 7.

III. DISCUSSION

The range of rates of change of f_0 with respect to air pressure measured in this experiment correspond reasonably well with the results of Van den Berg's experiments[2] with excised human larynges. They are also rather close to the rates of change computed by Flanagan and Landgraf[12] for an electrical analog of the larynx. Flanagan and Landgraf, in their analog, attempt to account for the energy transfers that occur when the vocal cords collide during the closing phase of the glottal cycle. They consider a "hard" and a "viscous" boundary condition. These two boundary conditions essentially correspond to elastic and inelastic collision. The analog model predicts that the fundamental frequency of phonation is a function of the tension of the vocal cords, the boundary condition for vocal cord collision, the subglottal air pressure, and the supralaryngeal vocal tract configuration. The supralaryngeal vocal tract configuration affects both f_0 and the glottal area waveform.

The Flanagan and Landgraf model predicts that for the hard boundary condition and subglottal air pressures between 4 and 8 cm H_2O, $\Delta f_0/\Delta P$ will be equal to 12.5 Hz/cm H_2O for an average f_0 of 135 Hz and 14 Hz/cm H_2O for an average f_0 of 200 Hz. For the "viscous" boundary condition and subglottal air pressures between 8 and 16 cm H_2O, the rate of change of f_0 predicted by the model is 3 Hz/cm H_2O for phonation

at an average f_0 of 110 Hz and 6 Hz cm H_2O for phonation at an average f_0 of 180 Hz. The range of values of $\Delta f_0/\Delta P$ derived from this model is 2.5 to 20 Hz/cm H_2O. The predictions of this model are. in general, supported by the experimental data presented in Figs. 3 and 7.

In the Ladefoged[4] and Öhman and Lindqvist,[3] studies on the relationship between f_0 and subglottal air pressure, the experimenters produced transient increases in subglottal air pressure by pushing the speaker's chest while he attempted to sing a steady note. Although the rates of change of f_0 with respect to air pressure measured in these experiments (5 and 2.5 Hz/cm H_2O, respectively) fall within the range measured in both this experiment and by Van den Berg,[2] it is possible that these values reflect the effects of laryngeal adjustments that may have compensated, in part, for the increase in the subglottal air pressure. Koike[13] notes that a blow or sudden pressure on the chest is likely to trigger a startle response, that is, a general adjustment of body posture and physiological activity. The relative timing of the subglottal air-pressure buildup and any possible compensatory laryngeal adjustments becomes uncertain if the increase in subglottal air pressure is simply one of the consequences of the startle response, rather than being the direct consequence of the push on the speaker's chest. The data of Öhman and Lindqvist,[3] in particular, seem to indicate that the rate of change of f_0 changes during the course of the air-pressure buildup. It is 10 Hz/cm H_2O during the first 75 msec and 2.5 Hz/cm H_2O thereafter. Sears and Davis[14] have found that feedback regulation in the respiratory system can occur within 50 msec. Kirchner[15], has, moreover, found that efferent receptors exist within the joints of the laryngeal cartilages. These receptors could possibly act as monitors of fundamental frequency in a feedback system.

The rates of change of f_0 with respect to air pressure measured in the present study are generally lower than those measured in the earlier study[5] where subglottal air pressure was correlated with fundamental frequency during the nonterminal portions of declarative sentences. The rates of change of f_0 measured in that study ranged from 16 to 22 Hz/cm H_2O. Three factors may account for these differences. The most obvious reason is that in the earlier study the laryngeal tension may not have been similar for all the points at which subglottal air pressure and f_0 were correlated. Indeed, it was apparent that the speakers often departed from the "archetypal" breath group, and variations in laryngeal tension did occur during the nonterminal portions

[12] J. L. Flanagan and L. Landgraf, "Self-Oscillating Source for Vocal-Tract Synthesizer," Proc. IEEE Audio Electroacoust. Group, 1967 Conf. Speech Commun. Processing, 54–62 (1967).

[13] Personal communication from Y. Koike, Inst. for Laryngol. and Voice Disorders, Los Angeles, Calif.

[14] T. A. Sears and J. N. Davis, "Control of respiratory Muscles during Voluntary Breathing," Proc. Conf. Sound Production in Man, New York Acad. Sci. (1968).

[15] J. A. Kirchner, "Laryngeal Reflexes and Voice Production," Proc. of Conf. Sound Production in Man, New York Acad. Sci. (1968).

of the breath groups. Errors may also have been introduced through the neglect of a second factor, the variations in f_0 that were caused by the interaction of the supralaryngeal vocal tract with the glottal output. Flanagan and Landgraf[12] in their model calculate that changes in vowel quality can cause changes in f_0 of 10 Hz at an average f_0 of 100 Hz. Peterson and Barney[16] and Swigart and Takefuta[17] have measured similar effects for natural speech.

The third factor that may account for the higher rates of change of f_0 noted during the production of sentences is the possibility that the different values reflect different laryngeal modes associated with speech and with singing. Some evidence exists that is consistent with the notion that the larynx is adjusted differently for singing and for speech. Ladefoged and McKinney[18] found different relationships between air pressure and fundamental frequency when speakers attempted to control pitch and when the speakers did not attempt to control pitch.

It is quite possible that the adjustments of the laryngeal musculature that are typical of singing, where the singer, of course, wants to maintain or control f_0, are rather different from those characteristic of speech where it is not necessary to control f_0 precisely. Indeed, it would be an advantage in singing to minimize the air-pressure dependence of f_0. In terms of the Flanagan and Landgraf model,[12] this could be done by simply using a viscous boundary. The use of a viscous boundary condition would also maximize the closed phase of the glottal volume velocity function, which would conserve air and maximize the high-frequency content of the glottal excitation's energy spectrum. Both of these adjustments would be desirable for singing since they would make it possible to produce louder sounds longer.

The fact that the relationship between f_0 and air pressure is not invariant over all modes of laryngeal activity makes it difficult, except for certain clear cases, to assign changes in f_0 with certainty to either adjustments of the laryngeal muscles or to changes in subglottal air pressure. The increase in f_0 that occurs at the end of a marked breath group (e.g., at the end of a YES–NO question in English) is one of the clear cases where it is possible to assign changes in f_0 to laryngeal activity. At the end of a marked breath group, f_0 usually increases although the subglottal air pressure decreases.[4,5] The increase in f_0 thus can only be due to laryngeal activity. The assignment of the terminal f_0 contour of the marked breath group to a laryngeal

maneuver is confirmed by electromyographic data. Ohala and Hirano,[19] for example, show that the activity of the crico-thyroid and lateral crico-arytenoid muscles increases at the end of a marked breath group. Since the studies of the behavior of excised larynges[1,2] show that the increased longitudinal tension placed on the vocal cords by the contraction of the crico-thyroid muscle will raise f_0, we can establish a causal relationship between the activity of this muscle and the rising f_0 contour at the end of the YES–NO question. The increased activity of the lateral crico-arytenoids however cannot always be directly correlated with a rising f_0 contour. Increases in medial compression of the vocal cords, which follow from increased activity of the lateral crico-arytenoids, however, cannot always be directly correlated with a rising f_0 contour. Increase in medial compression of the vocal cords can result in an increase in f_0 under certain conditions. However, increases in medial compression can sometimes lower f_0.[20] The larynx is a complex mechanism and it is necessary to consider other more direct evidence when the electromyographic activity of individual laryngeal muscles is analyzed.

IV. CONCLUSION

The fundamental frequency of phonation is a function of both the tensions of the various laryngeal muscles and the air-pressure drop across the larynx. In this experiment, a single male speaker attempted to phonate at steady pitches while an external device modulated the transglottal air pressure. The tension of his laryngeal muscles was presumably constant and the fundamental frequency of phonation f_0 thus followed the transglottal air-pressure variations. However, the rate of change of f_0 with respect to air pressure was not invariant. It varied from 3 to 18 Hz/cm H_2O. The sensitivity of f_0 to air-pressure variations, in other words, varied. These variations in the rate of change of f_0 encompass the rates previously measured in several independent studies. These data also support a recent quantitative model of laryngeal activity.[12] Greater variations in f_0 tended to occur at low levels of vocal effort and at high average fundamental frequencies. Auditory feedback did not appear to affect the variations in f_0.

The differences in the rate of change of f_0 with respect to air pressure rather seem to reflect different manners of phonation that, in turn, are the result of different ways of adjusting the larynx. The laryngeal muscles can adjust the longitudinal and medial tension of the vocal cords, the thickness of the vocal cords, the rest position of the vocal cords, and the mass that enters into the vibratory cycle. These adjustments, which determine the general aspects of the glottal waveform and

[16] G. E. Peterson and H. L. Barney, "Control Methods Used in a Study of the Vowels," J. Acoust. Soc. Amer. 24, 175–184, 1952.

[17] E. Swigart and Y. Takefuta, "The Produced and Perceived Pitch of American English Vowels," Proc. IEEE Audio Electroacoust. Group, 1967 Conf. Speech Commun. Processing, 273–277 (1967).

[18] P. Ladefoged and N. P. McKinney. "Loudness, Sound Pressure, and Subglottal Pressure in Speech," J. Acoust. Soc. Amer. 35, 454–460 (1963).

[19] J. Ohala and M. Hirano, "Studies of Pitch Change in Speech," Working Papers in Phonetics, UCLA, 80–84 (Nov. 1967).

[20] J. Van den Berg, "Vocal Ligaments versus Registers," Current Probl. in Phoniat. Logoped., 1, 19–34 (1960).

the mode of phonation, also appear to affect the rate of change of f_0 with respect to air pressure.

Recent studies of the intonation of speech[19,21] have claimed that laryngeal maneuvers are solely responsible for the fundamental frequency variations that typically occur during speech. These studies claim that changes in subglottal air pressure have an insignificant effect of fundamental frequency. The basis for these claims is the assumption that the rate of change of fundamental frequency with respect to transglottal air pressure never exceeds 3 to 5 Hz/cm H_2O. Our data indicate that this assumption is incorrect. The variations in fundamental frequency that always occur during speech are undoubtedly due to both variations in transglottal air pressure and laryngeal tension. The relative importance of these two mechanisms for changing fundamental frequency may vary for different modes of phonation.[22]

[21] R. Vanderslice, "Larynx vs. Lungs: Cricothyrometer Data Refuting some Recent Claims Concerning Intonation and Archetypality," Working Papers in Phonetics, UCLA, 69–80 (Nov. 1967).

[22] J. L. Flanagan in a recent study of a computer model of the larynx and vocal tract reported at the Kyoto Speech Symposium, Kyoto Japan, 31 August 1968, found that the rate of change of

but both factors must be accounted for in the analysis of intonation.

ACKNOWLEDGMENTS

fundamental frequency with respect to transglottal air pressure is also a function of the acoustic load on the larynx. As the configuration of the supralaryngeal vocal tract changes, the rate of change of fundamental frequency with respect to air pressure varies from 2.5 to 20 Hz/cm H_2O, all other things being equal. For vowels like /u/ and /i/, the larynx is most sensitive to air-pressure variations. The larynx is least sensitive for vowels like /a/, where the first formant frequency is relatively high. The effect of the speakers phonating into a tube in this experiment thus, in all liklihood, was to keep the sensitivity of the larynx to air pressure variations at a high level. During the production of normal speech, the effects of the supralaryngeal vocal tract on the dynamic characteristics of the larynx must be taken into account insofar as they affect both the average fundamental frequency[12,16,17] and the rate of change of fundamental frequency with respect to air-pressure variations.