Vocal Fold Dynamics for Frequency Change

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Summary: This article provides a review of data drawn from a series of related experiments to demonstrate how frequency change (Δf_0) is accomplished in the modal register. The research cited involves studies of (1) laryngeal size, (2) vocal fold length, (3) vocal fold thickness, and (4) subglottic pressure; new data describe their effect on vocal fold mass. It was found that changes in these dimensions (1) explain how the shifts in frequency are accomplished, (2) establish the way vocal fold mass can be measured, and (3) strongly support the aerodynamic-myoelastic theory of phonation.
Key Words: Vocal fold dynamics–Frequency change–Vocal folds–Fundamental frequency–Aerodynamic-myoelastic theory–Phonation–Laryngeal size–Vocal fold length–Vocal fold thickness–Subglottic pressure–Vocal fold mass–Modal register.

INTRODUCTION

Although a number of authors have addressed the issue of how the larynx—and especially the vocal folds—operate to vary fundamental frequency (F_0) in speech and singing, only tentative explanations can be found. The present effort attempts to remedy this deficit. To do so, data that were collected over a period of some years are now being organized to support a model. They also will be used to assess certain aspects of the aerodynamic-myoelastic theory (ADMET) of phonation.[1]

A PERSPECTIVE

The difficulty in developing a model of the desired type is that because there are many dimensions to "voice," it would be impossible to include them all. For example, normal voice, vocal training (of all types), and voice disorders (due to disease, behaviors, and so forth) create several of the many complex continua that exist; so too do the different registers and ranges of voice as well as the extent and nature of vocal intensity and voice quality. Indeed, the complexity of phonation and its varying dimensions extends in many directions.

Accordingly, and to provide a reasonably comprehensive framework for this project, certain limitations will be observed. Specifically, the focus will be on a "core" system rather than one of many dimensions. It will be limited to (1) the normal voice exclusive of any kind of specialty training—disorders, disease, or damage; (2) the adult voice, exclusive of those of children, youths, and the elderly; and (3) the modal register only[2]; no attempt will be made to include loft or falsetto on the high frequency end or vocal fry, pulse or the mixed voice associated with low frequencies. The primary reason for these limitations is that healthy adults phonating in the modal register create, by far, the most common type of phonation. Of even greater importance is that more research has been carried out in this area than on any of the other potential relationships. Finally, these limitations should assist in establishing a reasonable baseline for a model.

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The presentation will be initiated with data on laryngeal size followed by consideration of vocal fold length, vocal fold thickness, and airflow/pressure variation. Many of the experiments relevant to the first three of these segments were carried out by the undersigned.

Finally, it also should be noted that the research on which the cited processes/model will be based was conducted, almost exclusively, during the second half of the 20th century. Because of that time frame and because the present effort results from a coordinated program of related experiments, the material to follow will be drawn from data published during that period.

LARYNGEAL SIZE

First, information about laryngeal size, as related to sex and frequency range, should be useful in providing a perspective for the investigations to follow; that is, those on vocal fold length, thickness, and mass. In this regard, an investigation[3] was carried out to provide just such information. Up until the initiation of that project, most attempts to quantitatively relate laryngeal dimensions to gender, age, voice level, and so forth had been based on either simple observations or by dissection of cadaver preparations.[4–6] Although observations of males and females were found to suggest significant gender differences, little actual data had been provided to show if size variations within each sex also were anatomically "correlated" with voice. Moreover, even the data, which were available were vulnerable to the criticism that may be leveled at virtually all analyses of external measures or cadaver preparations, that is, that they do not adequately represent phonation in the first case or represent living tissue in the second.

The approach used in this investigation was to study a population of live individuals by means of lateral soft-tissue X-rays. Four groups of six subjects each were selected from healthy volunteers aged 18–29 years. The groups were males with low-pitched voices (LM) (range: C_2–D_5); males with high-pitched voices (HM) (range: G_2–F_5); females with low-pitched voices (LF) (range: B_2–A_5); and females with high-pitched voices (HF) (range: G_3–E_6). Selection criteria[7,8] required that subjects be free of speech or voice defects, had received no formal training in singing, and exhibited the ability to perform the phonatory tasks necessary for this, plus other related, experiments. Note also that the HM and LF subjects had similar frequency ranges.

A standard lateral X-ray procedure was adapted to permit accurate laryngeal size measurements. The equipment used

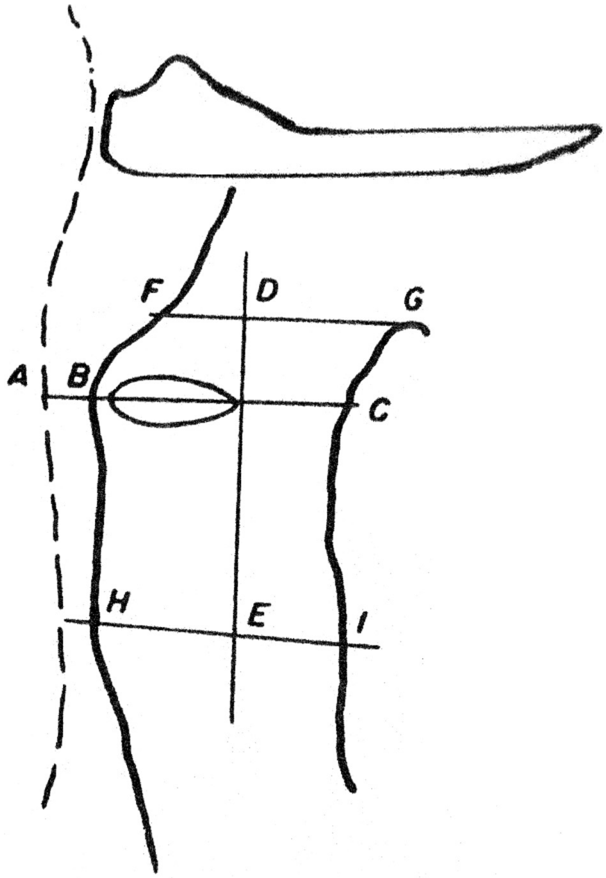

FIGURE 1. Tracing of a lateral X-ray film showing the indices (F-G-I-H) of general laryngeal size and the reference lines established for measuring A-P (A-C and B-C) and vertical (D-E) distances.

was a Picker unit; padding and cork blocks were used to position the subject, and standard corrections were used to compensate for variations in enlargement. The size data were based on measurements of outlines of the walls of the laryngeal pharynx (Figure 1). Differences (Table 1) among the subject groups were statistically significant (re: analysis of variance) with all but two critical differences also significant. Thus, it was shown that individuals with low-pitched voices could be expected to have larger laryngeal tracts than individuals exhibiting higher pitch ranges. It also was shown that gender differences also constitute a powerful variable, that is, that males will have larger laryngeal structures than females although they may exhibit similar pitch ranges.

VOCAL FOLD LENGTH

The next step was to assess vocal fold length as a function of sex and modal pitch range. To do so, the present author[9] first carried out relevant research on the same group of subjects studied in the preceding experiment. Subsequently, other groups, plus the same and other relationships, were addressed.

First investigation of vocal fold length

As stated, this experiment involved the population cited above. In this instance, however, subjects had their vocal folds photographed when they were abducting them and then when

TABLE 1.
Means of Four Measures (in mm) of Laryngeal Size, for Each of the Four Groups, With CDs Necessary for Significance at the 5% Level

	Subjects				
Measures	Low Male	High Male	Low Female	High Female	CD
AP-1	34.1	30.4	26.6	25.7	2.12
AP-2	24.2	21.2	16.5	15.1	1.86
Vertical	36.7	31.7	26.9	20.8	2.19
Area	715.6	606.0	405.0	301.0	60.62

Notes: There were six subjects in each group.
Abbreviation: CD, critical differences.

phonating pitches were at low (10%), medium (25%), high (50%), and falsetto (85%) levels with respect to their total range. However, because falsetto is outside of the purview of this research, only the first three levels will be considered here.

Until the time of this experiment, essentially no *comprehensive* investigations had been carried out directly on just how pitch (F_0) changes were accomplished. Vocal fold length was a possibility with some authors suggesting that it was this dimension which was varied, whereas Negus[6] countered that such changes were not possible. On the other hand, Moore[10] and Farnsworth[11] reported observing some sort of vocal fold lengthening-frequency relationships in their ultrahigh-speed motion pictures (see also Moore and von Leden[12]). Furthermore, both Irwin[13] and Brackett[14] had sometimes found similar, if somewhat varying, increases.

Of course, individuals attempting research of this type faced a number of serious challenges. Among them were problems such as visualizing the vocal folds in their entire length, effectively photographing them and then measuring them with reasonable precision. At issue, especially, was variation in "lens-to-field distance", that is, the distance between the folds and the photographic film. This variable fluctuated both because of differences in an individual's anatomic size and because the larynx was *sometimes* seen to rise with increases in pitch. Because the size of the photographic image is (in part) a function of these distances, it follows that measurements on laryngeal films could be subject to error, that is, if suitable corrections were not made.

These problems were addressed[9] by using updated systems, new measurement techniques, and by training the subjects to better expose their folds as they tolerated the attendant discomfort. The equipment consisted of a mounted laryngeal mirror, a parabolic "head" mirror (directing the light), a 500-W light source (with condensing lens and prism), and an Eastman Cine-Kodak 16-mm motion picture camera with a 4-in telephoto lens. A motion picture camera was used to permit selection of the optimum exposures for measurement. Control of subjects' F_0 was obtained by means of a reference tone at the required frequency level provided by an ordinary chromatic pitch pipe.

Figure 2 provides a drawing of the image most often available. Of the possible measurements, those employed in this