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Acoustic Impedance of an Artificially Lengthened and Constricted Vocal Tract

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Summary: Voice training techniques often make use of exercises involving partial occlusion of the vocal tract, typically at the anterior part of the oral cavity or at the lips. In this study two techniques are investigated: a bilabial fricative and a small diameter hard-walled tube placed between the lips. Because the input acoustic impedance of the vocal tract is known to affect both the shaping of the glottal flow pulse and the vibrational pattern of the vocal folds, a study of the input impedance is an essential step in understanding the benefits of these two techniques. The input acoustic impedance of the vocal tract was investigated theoretically for cases of a vowel, bilabial occlusion (fully closed lips), a bilabial fricative, and artificially lengthening the tract with small diameter tubes. The results indicate that the tubes increase the input impedance in the range of the fundamental frequency of phonation by lowering the first formant frequency to nearly that of the bilabial occlusion (the lower bound on the first formant) while still allowing a continuous airflow. The bilabial fricative also has the effect of lowering the first formant frequency and increasing the low-frequency impedance, but not as effectively as the extension tubes. **Key Words:** Vocal tract—Impedance—Inertance—Resonance tubes—Voice training techniques.

It has long been common practice in voice training to make use of vocal exercise techniques that involve partial occlusion of the vocal tract. While the techniques vary, the occlusion is typically within the front part of the oral cavity or at the lips. For example, Aderhold[1] described improvements in vocal resonance following exercises of phonating while holding one's hand at the lips, partially covering the mouth. Furthermore, Aderhold[1] cited Engel[2] as suggesting that in high-quality voice production there should be only a narrow pathway between the tip of the tongue and the alveolar ridge. Similarly, Lessac[3] promoted the use of the "y-buzz" for vocal training which is a closed front vowel with a tight linguopalatal constriction and narrow spacing between the upper and lower teeth; the lips are also slightly protruded. The "y-buzz" is said to provide a rich vocal quality in the *lower* ranges of the voice, protects against strain and "throatiness," and induces a relaxed vocal production. Other techniques have made use of voiced fricatives[4-6] and voiced bilabial trills[6] which again are created by narrow constrictions in either the frontal section of the oral cavity (fricatives) or at the lips (trills).

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The use of the bilabial fricative [β] as a vocal exercise has been studied by Laukkanen et al.[7] Their study, which involved 6 participants, showed that both glottal flow (inverse filtered) and electroglottographic (EGG) waveforms changed during production of [β:] such that the open phase of the glottal cycle was increased and the slope of the glottal flow pulse near closure was reduced. Both observations indicate an interaction of the vocal tract pressures with the oscillatory mechanics of the vocal fold vibration. Bickley and Stevens[8] reported similar findings in their study of EGG waveforms produced by 6 subjects with artificially imposed constrictions (hardwalled tubes approximately 1 cm long and of various diameters) at the lips during voicing. For constrictions with cross-sectional areas smaller than 0.1 cm^2, the open phase of the glottal cycle was shown to increase by over 20% relative to an unconstricted segment. Similar increases were reported for the same 6 subjects during production of the voiced fricatives v and ð. Constrictions with area greater than 0.2 cm^2 had little effect on altering the open phase duration.

While the Bickley and Stevens[8] study did not specifically address vocal exercise or voice therapy, it did show that vocal fold oscillation can be influenced by articulatory or artificially imposed supraglottal constrictions (as did Laukkanen et al[7]). It is of interest to note that the use of artificial extensions and constrictions of the vocal tract for therapeutic purposes were apparently proposed as early as 1899 by Spieβ.[9] Both Gundermann[10] and Habermann[11] make mention of Spieβ's[9,12,13] technique of humming into a tube 12 cm in length and 1 cm in diameter. Gundermann[10] and Habermann[11] also credit Stein[14] with reviving interest in Spieβ's tube phonation techniques. Sovijärvi[15,16] reported using tubular vocal tract extensions (he called them "resonance tubes") which terminated in a volume of water as a treatment for hypernasality. Presumably, successful phonation through the tube and into the water (making the water bubble) would require full closure of the velum, thus providing an exercise against a hypernasal condition. Sovijärvi[15,16] also found that for some patients phonation was disturbed by the presence of the tube, while others experienced an ease of phonation. However, if the length of tube was lengthened or shortened for those who had phonation disturbances, phonation became much easier. Thus, the optimum tube length varied from person to person.

This method of using tubes to extend and constrict the vocal tract is still used in Finnish voice training and therapy[17,18]; the tubes can be used without terminating them into a volume of water. However, until recently, little information has been reported with regard to the possible scientific reasons that phonation into tubes or articulated constrictions may be a useful voice therapy. Laukkanen et al have undertaken a series of studies[19-22] intended to provide an understanding of these methods but have so far produced inconclusive and sometimes contradictory results.

Common to all of the training and therapy methods cited above is a reduction of the cross-sectional area of the vocal tract at or near the lips. In the case of the resonance tube approach, the constriction is also coupled with a lengthening of the vocal tract. For all of these cases, the acoustic *impedance* of the vocal tract, as "seen" from the glottis, will be altered relative to a vowel-like articulation. But what is "impedance"? In general, impedance describes how difficult it is to make a system move. However, this type of description is a bit misleading because it brings to mind images of, for example, the difficulty of pushing a refrigerator across a concrete floor. High impedance is undoubtedly encountered in this case but primarily because of the large amount of friction (or resistance) between the refrigerator base and the floor; nearly all of your pushing energy would be burned up in this resistance. But impedance is not composed solely of resistance. It has a second component called reactance which, unlike resistance, stores energy rather than removing it and this may actually be helpful for moving a system. One might experience the effects of reactance by attaching wheels to the base of the refrigerator so that only an initial (but difficult) push is needed to send it moving across the floor due to its inertia. A high impedance still exists but the pushing energy in this case is stored as inertial energy (inertive reactance) rather than being burned up and removed as in the case of resistance.

Acoustic impedance is analogous to these examples except that it describes the resistances and reactances of wave motion in air. As such, it provides the "acoustic load" that is imposed upon the voice source (ie, aerodynamic and mechanical properties of vocal fold vibration). It is well known that the vocal tract input impedance can significantly affect the glottal flow pulse shape[23-25] as well as influencing the oscillatory characteristics of the vocal folds.[26-28] Furthermore, it has been shown that increased supraglottal impedance due to a reduction in epilaryngeal cross-sectional area can lower the phonation threshold pressure,[29] suggesting that the start-up of vocal fold oscillation may be eased by increased tract impedance. In particular, it is the inertive reactance that is most important for facilitating vocal fold vibration. It is assumed that high impedance is a desirable quality based on the previously cited work. However, there would obviously be a limitation to this since an overly large impedance would likely halt phonation. The purpose of this paper is to theoretically examine how supraglottal constrictions and artificial extensions of the vocal tract affect the acoustic impedance as "seen" from the glottis.

METHODS

To investigate the possible effects of constrictions or tube extensions of the vocal tract, input impedances were calculated for seven different vocal tract configurations. The configurations are represented in the form of a vocal tract area function (ie, the cross-sectional area as a function of distance from the glottis) and are shown in Figure 1. An alternative view is

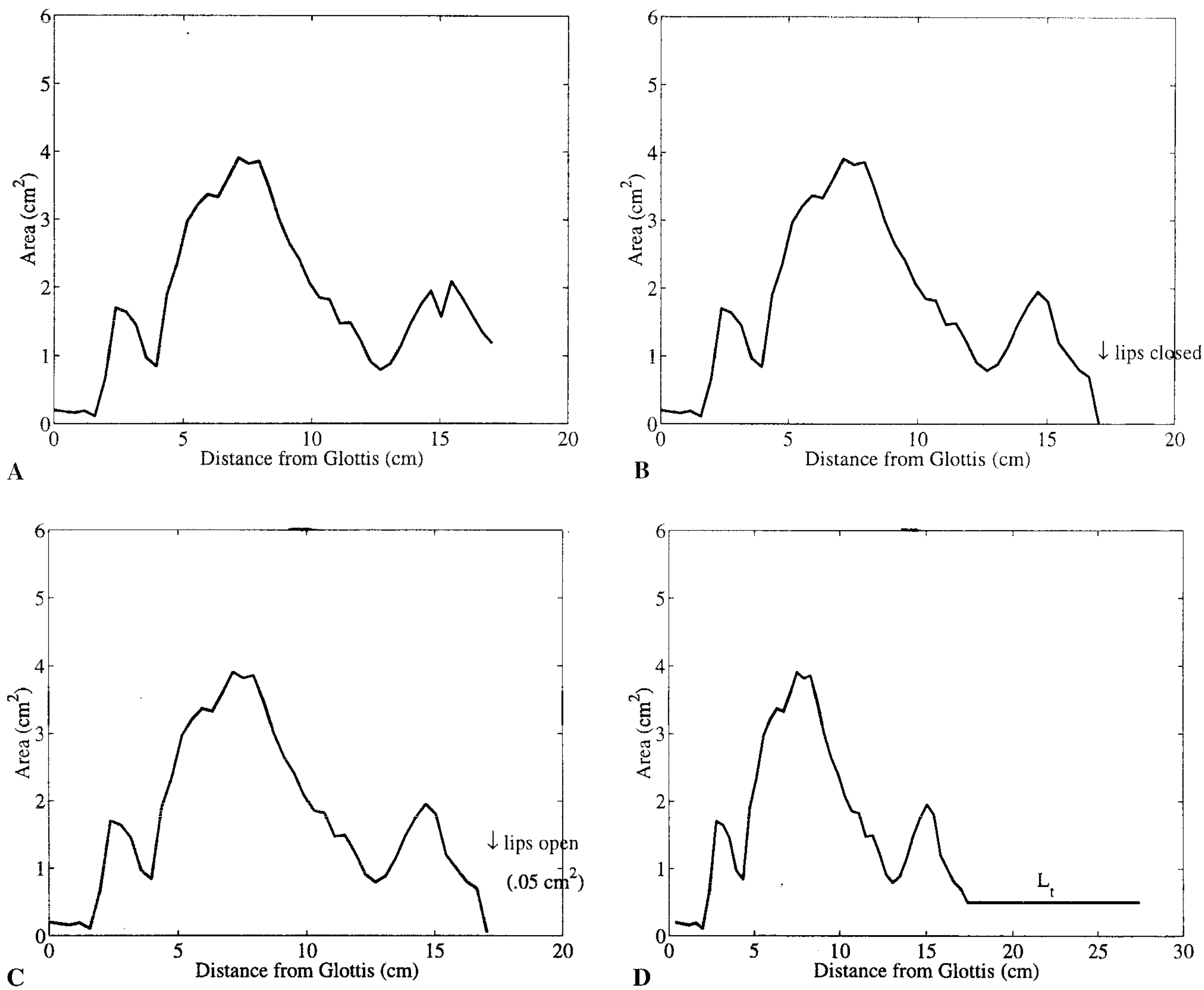

FIG. 1. Area functions used in this study; (**A**) vowel [ɪ] based on Story et al,[30] (**B**) bilabial plosive [b$_I$]; (**C**) bilabial fricative [β:], (**D**) vowel [ɪ] modified with an extension tube of cross-sectional area 0.5 cm^2 and length L_t (input impedances were calculated for four different values of L_t: 10, 30, 50, 100 cm).

given in Figure 2 where each area function is plotted as a set of equivalent diameters in the sagittal plane. This is perhaps a more intuitive perspective for readers unfamiliar with traditional area functions; however, both Figures 1 and 2 present the same information. The first configuration (Figures 1A and 2A) is a reference vowel [ɪ]; this conclusion is based on information reported in Story et al.[30] The choice of reference vowel is somewhat arbitrary but represents a likely tongue position during production of the vocal tract modifications that follow. All of the other area functions are simple modifications of the extreme front portion of this reference [ɪ]. Thus, the second and third configurations (Figures 1B and 2B and Figures 1C and 2C) represent possible realizations of the bilabial plosive [b_I] and the bilabial fricative [β:], respectively. Finally, Figures 1D and 2D show the vowel [ɪ] modified with an extension tube of cross-sectional area 0.5 cm² and length L_t. Input impedances were calculated for four different values of L_t: 10, 30, 50, 100 cm.

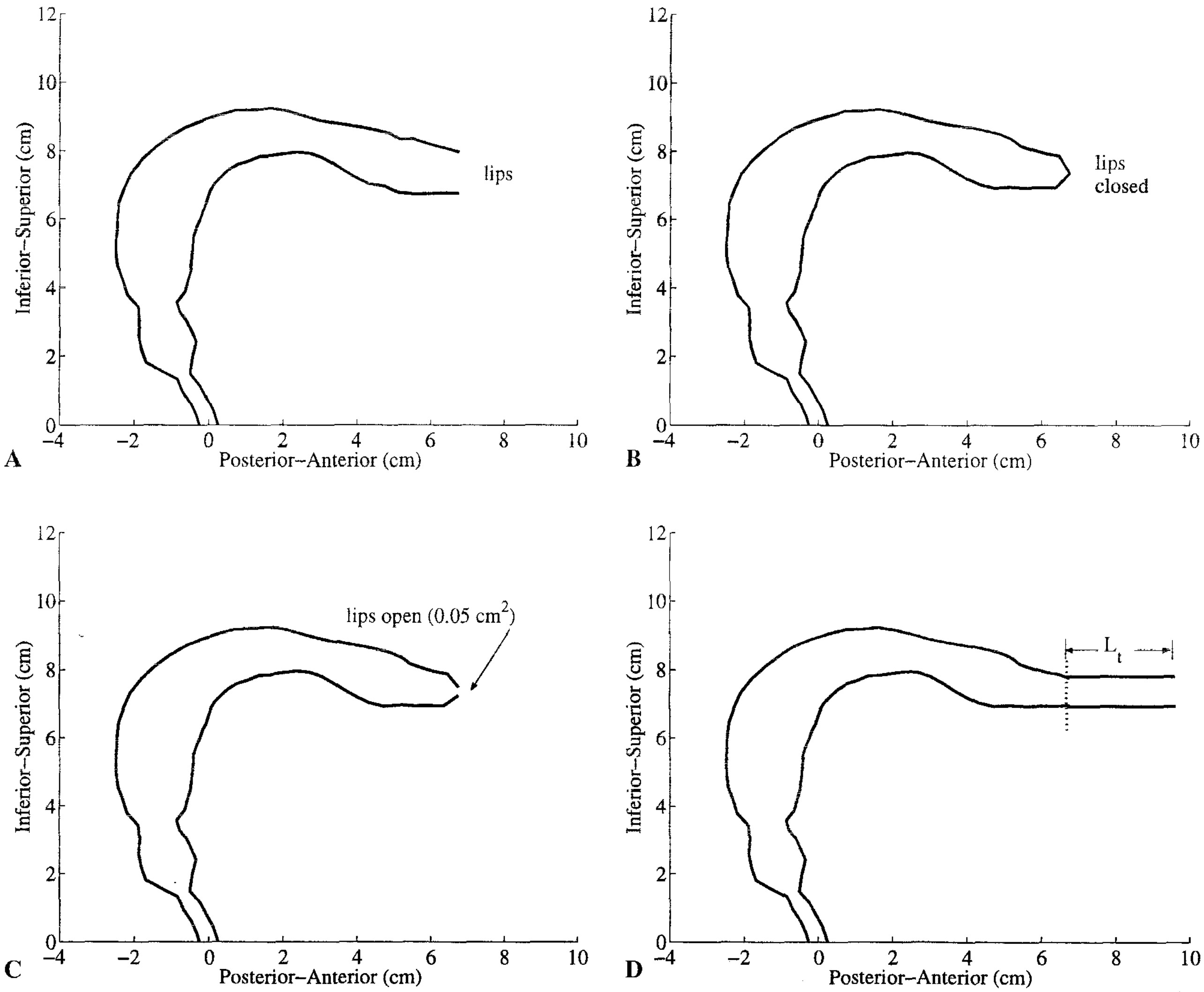

FIG. 2. Area functions used in this study plotted as equivalent diameters about a sagittal vocal tract profile; (**A**) vowel [ɪ] based on Story et al[30]; (**B**) bilabial plosive [b_I]; (**C**) bilabial fricative [β:]; (**D**) vowel [ɪ] modified with an extension tube of cross-sectional area 0.5 cm² and length L_t (input impedances were calculated for four different values of L_t: 10, 30, 50, 100 cm).

A transmission line model based on Sondhi and Schroeter[31] was used to calculate the frequency-dependent input acoustic impedance of the vocal tract. It is a general chain matrix approach written as

$$\begin{pmatrix} P_{out} \\ U_{out} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} P_{in} \\ U_{in} \end{pmatrix} \quad (1)$$

where P_{in} and U_{in} are pressure and volume velocity at the glottal end of the vocal tract and P_{out} and U_{out} are similar quantities but at the lip termination. The matrix including the elements A, B, C, and D represents the propagation of acoustic waves through the vocal tract. For computational purposes the area function (eg, Figure 1A) is approximated by a discrete series of concatenated cylindrical tubelets of length Δl and cross-sectional area a. Figure 3 shows the discretized form of the area function in Figure 1A.

The wave-propagation matrix for the entire vocal tract (Eq. 1) must be built up from similar matrices determined for each tubelet section of the discretized area function. The chain matrix elements for each tubelet are

$$\begin{aligned} A &= \cosh\left(\tfrac{\sigma\Delta l}{c}\right) & B &= -\tfrac{\rho c}{a}\gamma\sinh\left(\tfrac{\sigma\Delta l}{c}\right) \\ C &= -\tfrac{a}{\rho c\gamma}\sinh\left(\tfrac{\sigma\Delta l}{c}\right) & D &= \cosh\left(\tfrac{\sigma\Delta l}{c}\right); \end{aligned} \quad (2)$$

The variable c is the speed of sound and ρ is the density of air while the other variables are defined to be

$$\gamma = \sqrt{\frac{r + j\omega}{\beta + j\omega}} \quad (3)$$

and

$$\sigma = \gamma(\beta + j\omega) \quad (4)$$

where

$$\beta = \frac{j\omega(2\pi F_T)^2}{(j\omega + r)j\omega + (2\pi F_\omega)^2} + \alpha \quad (5)$$

and

$$\alpha = \sqrt{j\omega q} \quad . \quad (6)$$

The variable ω is the radian frequency which is equivalent to $2\pi f$ where f is frequency in cycles per second or hertz (Hz). The j, which is conventionally defined as $\sqrt{-1}$, allows for separation of the so-

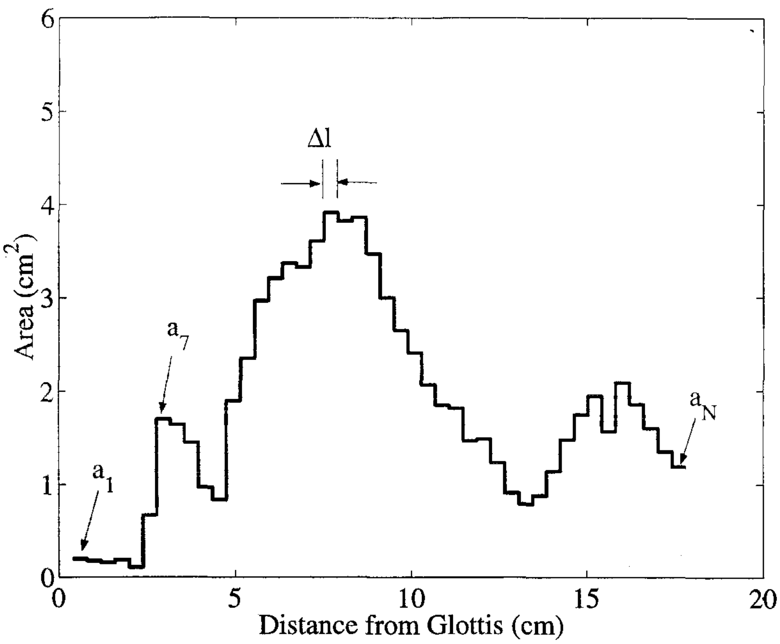

FIG. 3. Discretized form of the area function in Figure 1A represented by concatenated "tubelet" sections.

called real and imaginary parts of the propagating wave; any quantity multiplied by j is considered to be included in the imaginary part. The parameters r and F_w are related to the yielding properties of the vocal tract wall and represent the ratio of wall resistance to mass and the mechanical resonance frequency of the wall, respectively. Following Sondhi and Schroeter[31] the values for r and F_w are set to $r = 408$ rad/s and $F_w = 15$ Hz. F_T is the lowest resonant frequency of the tract when closed at both the glottal and lip ends. This is a lower bound on the first formant frequency when the shunting effect of the yielding wall is included; for a hard-walled tract the lowest resonant frequency would be zero. According to Fujimura and Lindqvist,[32] a typical closed tract formant frequency is about $F_T = 200$ Hz. The parameter q is a correction for thermal conductivity and viscosity, which is set to $q = 4$ rad/s. These parameters were held constant throughout this study except for the cases with the tubular extensions. For these, the portion of the area function that is "vocal tract" is set to the values stated above. For the tube section the walls are rigid and the parameters r, β, and α are all set to zero.

Chain matrix elements are calculated for each tubelet in the area function and then multiplied, in matrix fashion, to produce the composite matrix for the entire vocal tract. Thus, if the matrix for the nth tubelet is

$$K_n = \begin{pmatrix} A_n & B_n \\ C_n & D_n \end{pmatrix} \tag{7}$$

then the composite matrix is determined by

$$K_{\text{tract}} = K_N\, K_{N-1} \ldots K_2\, K_1 = \begin{pmatrix} A_{\text{tract}} & B_{\text{tract}} \\ C_{\text{tract}} & D_{\text{tract}} \end{pmatrix} \tag{8}$$

giving a final relationship of pressure and volume velocity at the inlet end of the vocal tract to those at the output end

$$\begin{pmatrix} P_{\text{out}} \\ U_{\text{out}} \end{pmatrix} = \begin{pmatrix} A_{\text{tract}} & B_{\text{tract}} \\ C_{\text{tract}} & D_{\text{tract}} \end{pmatrix} \begin{pmatrix} P_{\text{in}} \\ U_{\text{in}} \end{pmatrix} . \tag{9}$$

The *input impedance*, calculated as the ratio of input pressure to input volume velocity

$$Z_{\text{in}} = \frac{P_{\text{in}}}{U_{\text{in}}} , \tag{10}$$

is a complex quantity consisting of real and imaginary parts. The real part is typically called *resistance* while the imaginary part is called *reactance*. The resistance represents all the mechanisms that remove energy from the vocal tract during wave propagation. The various mechanisms that store energy are represented by the reactance. As mentioned above, the input impedance gives an indication of the frequency-dependent acoustic "load" that confronts the voice source during its operation.

In addition to the vocal tract contributions, the total input impedance Z_{in} also includes the effects of acoustic radiation from the lip end of the vocal tract to the outside air. The radiation is included as an additional impedance called the radiation impedance Z_L and is approximated as a vibrating piston in an infinite baffle,[33]

$$Z_L = \frac{j\omega RL}{R + j\omega L} = \frac{\omega^2 RL^2 + j\omega R^2 L}{R^2 + \omega^2 L^2} \tag{11}$$

where

$$R = \frac{128 Z_M}{9\pi^2} \tag{12}$$

and

$$L = \frac{8bZ_M}{3\pi c} . \tag{13}$$

The variable b is the equivalent radius of the lip termination, $b = \sqrt{\frac{A_M}{\pi}}$ and Z_M is the characteristic acoustic impedance of the final section of the vocal tract, $Z_M = \frac{\rho c}{A_M}$. The radiation impedance consists of a reactive part representing that portion of the sound wave that is returned to the vocal tract (ie, stored) and a resistive part indicating the portion that propagates into the outside air.

To determine an expression for Z_{in} that contains only the final matrix elements [Eq. (8)] and the radiation impedance, it is assumed that the vocal tract output pressure at the lips P_{out} can be written as the output volume velocity through the radiation impedance

$$P_{\text{out}} = Z_L U_{\text{out}} . \tag{14}$$

Substituting Eq. (14) into Eq. (9) and solving for Z_{in}, yields the final expression for input impedance,

$$Z_{in} = \frac{D_{tract}Z_L - B_{tract}}{A_{tract} - C_{tract}Z_L} \quad . \tag{15}$$

RESULTS

Before showing the impedance calculations for the perturbed vocal tract configurations, a brief general explanation of impedance curves will be given. Figure 4A shows a pair of curves based on calculations for a 17.5-cm-long uniform tube with cross-sectional area 3 cm^2 in the region of F_1; the frequency range shown is 0-1000 Hz. The solid line represents the reactive part of the impedance (reactance) which indicates storage of acoustic energy within the vocal tract. The dashed line is the resistive part (resistance) and indicates a dissipation of acoustic energy both within the vocal tract (eg, viscosity, heat, and yielding wall losses) and through the radiation characteristics present at the mouth. When the reactance is positive, as it is for the first half of the curve, it is considered to be *inertive* or masslike. When negative, the reactance is *compliant* or springlike. The frequency of resonance is located at the point where the reactance is equal to zero. Note that this point also coincides with the maximum value of the resistance curve. Thus, resonance occurs when nearly all of the energy in the vocal tract is dissipated by the various resistive mechanisms and almost none is stored in the reactive part of the impedance. Because resonance is generally thought to enhance a frequency band of vocal sound it may seem counterintuitive that most of the energy in the vocal tract is dissipated at resonance. However, recall that a portion of the resistive part of the input impedance belongs to the radiation characteristic at the lip end. It is dissipation into this resistance that carries sound from the speaker to a listener. Thus, at the resonance frequency, higher sound levels can be radiated than at nonresonance frequencies.

Figure 4B shows the magnitude of the impedance, which is the square root of the sum of the squares of the resistance and reactance components in Figure 4A (plotted logarithmically in dB in this figure). The peak of the magnitude curve corresponds to the resonant frequency. It might also be pointed out that another quantity called the "transfer function" is often used to predict the frequency-dependent sound output characteristics of a given vocal tract shape. The transfer function is the ratio of radiated sound pressure to the glottal volume velocity and is sometimes referred to as the formant spectrum. While the transfer function is of great importance for studying the output of the vocal tract it is less useful for understanding the acoustic loading of the voice source.

Input impedance curves for the [ɪ], the bilabial fricative [β:], and the bilabial plosive [b_I] are shown in Figure 5; Figure 5A shows the impedance magnitudes plotted logarithmically in dB while Figures 5B and 5C are the reactance and resistance curves, respectively. The curves are shown with a frequency range of 0-500 Hz. This limited range was chosen because the interest is in observing the impedance in the proximity of typical fundamental frequencies of phonation. The impedance magnitude of the [ɪ] has its first formant frequency at 475 Hz (far right-hand side of the graph) while the [β:] and the [b_I] have first formants at progressively lower frequencies of 326 Hz and 190 Hz, respectively. Between about 100 Hz and 200 Hz (a typical range of male phonation frequencies), the input impedance curves are higher for the [β:] and [b_I] than for [ɪ]. This is also borne out by the reactance and resistance curves (Figures 5B and 5C) which, in this 100-200 Hz frequency range, show progressively higher levels for the [β:] and [b_I] in comparison to [ɪ]. If the optimal condition for phonation is that of maximum inertive reactance, the fundamental phonation frequency should coincide with the *peak* of the reactance curve (see Figure 5B). Note that this point is not located at F_1 but occurs at a frequency somewhat below it.

In Figure 6, a similar set of curves is shown, but for two cases of the hard-walled tube extension of the vocal tract (tube lengths: 10 and 30 cm); as the bilabial plosive [b_I] had the highest impedance (in the 100-200 Hz frequency range) of the cases in Figure 5, its impedance curves are also shown here for comparison purposes. In the region of 100-200 Hz, both tube cases show impedances that are less than that of the [b_I] but higher than the impedances for the bilabial fricative [β:] and [ɪ] shown above.

Impedance curves for cases of two longer tubes (50 cm and 100 cm) along with those for the [b_I] are

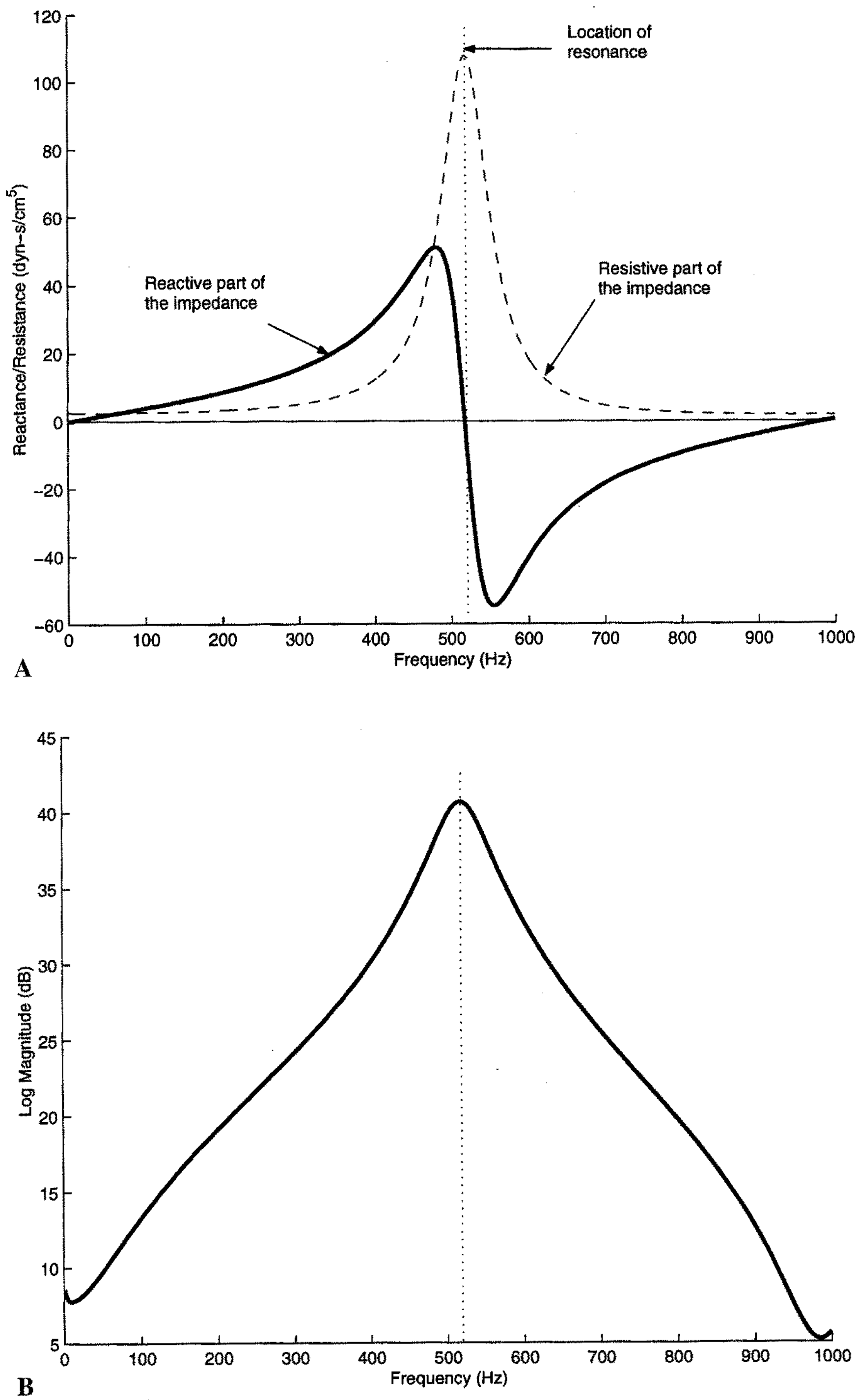

FIG. 4. Demonstration of impedance curves calculated for a uniform tube of 3 cm^2 in cross-sectional area and 17.5 cm in length; (**A**) reactance (*solid line*) and resistance (*dashed line*), (**B**) log magnitude of the impedance shown in decibels. The resonance (or formant) frequency occurs when the reactance equals zero and resistance is maximum.

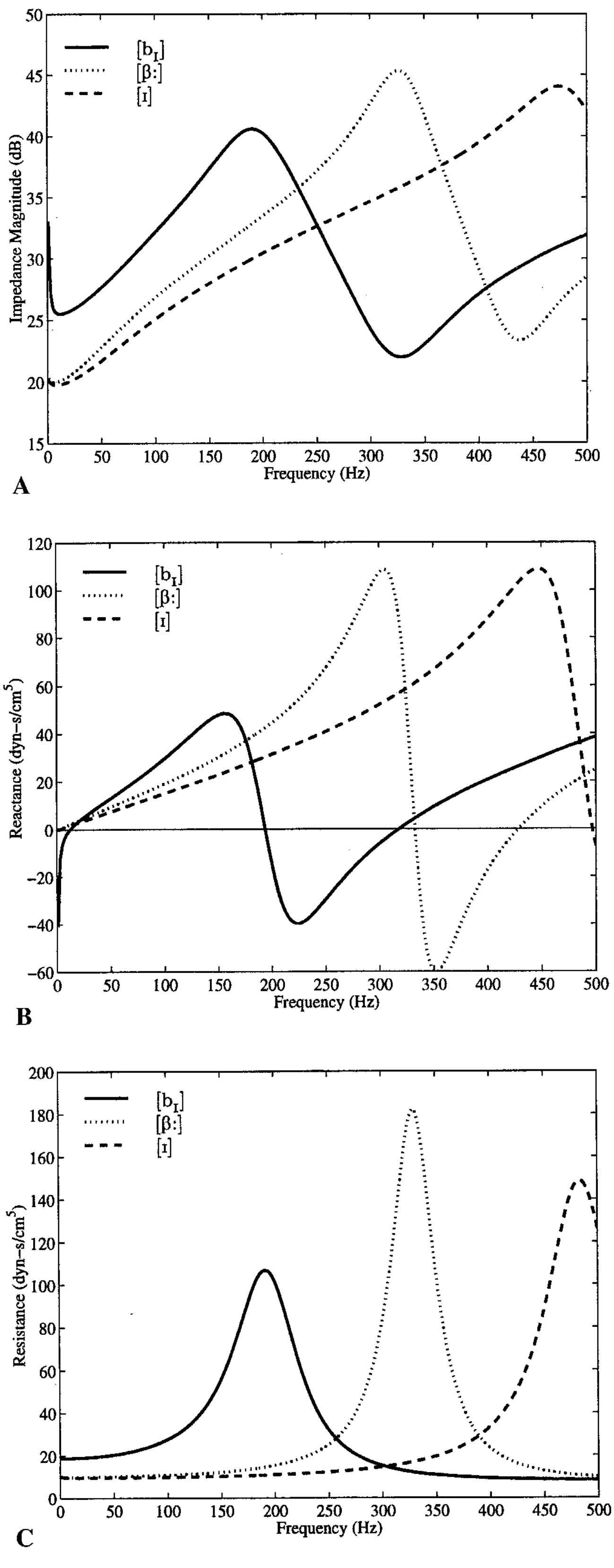

FIG. 5. Input impedance curves for the vowel [ɪ] (*dashed line*), the bilabial fricative [β:], and the bilabial plosive [b_I]. (**A**) Log magnitude of the impedance, (**B**) reactance, and (**C**) resistance. The spectra are shown with a frequency range of 0-500 Hz.

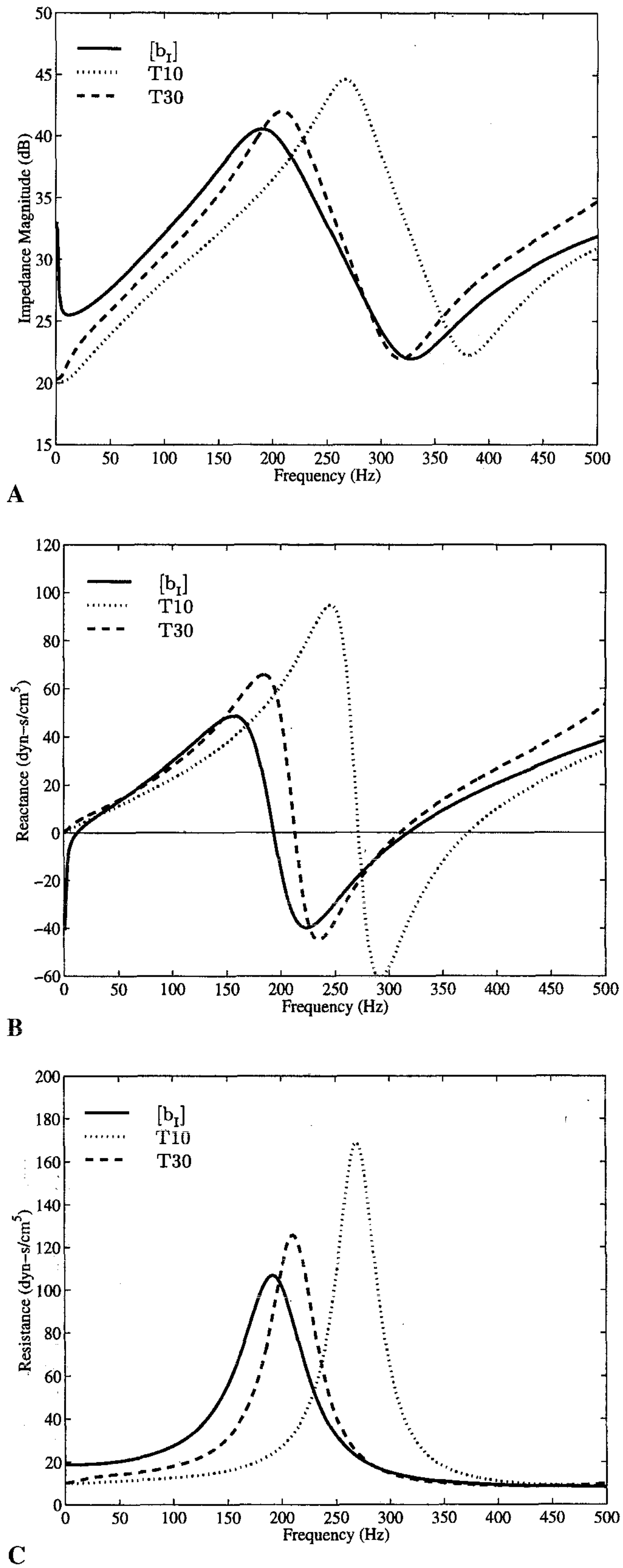

FIG. 6. Input impedance curves for the bilabial plosive $[b_I]$ (*solid line*) for two cases of the hard-walled tube extension of the vocal tract [tube lengths: 10 cm (*dotted line*), 30 cm (*dashed line*)]; (**A**) Log magnitude of the impedance, (**B**) reactance, and (**C**) resistance. Because the bilabial plosive $[b_I]$ had the highest impedance of the cases in Figure 5, its impedance curves are shown for comparison purposes.

shown in Figure 7. In the case of the 50-cm tube extension (T50), the first formant has been lowered such that the impedance is nearly equivalent to that of the [b_I] for F_1 and below. For the 100-cm tube extension (T100), the first formant has been further decreased so that it is lower in frequency than that of the [b_I]. Between about 95 and 135 Hz the impedance magnitude of the T100 case slightly exceeds that of the [b_I] and the T50 case. However, a study of the reactance and resistance curves (Figures 7B and 7C) indicates that the positive part of the reactance curves below T100's first formant peak are essentially at the same level for all three cases. It is the resistance that varies among the three. Thus, while increasing the tube length does lower the first formant frequency, there is no gain in the positive reactance that would be imposed on the vibrating vocal folds. This is due to the presence of the yielding wall. Additionally, the T100 case shows the presence of multiple resonances within the range of phonation frequencies. With the exception of very low phonation frequencies (below about 115 Hz), phonation could be difficult for this case because of the wide variation in the reactance curves; that is, alternation between inertive (positive) and compliant (negative) reactance.

DISCUSSION

This study has demonstrated changes in vocal tract input impedance that can be expected with the use of vocal tract extension tubes and other partial occlusions for voice training. The [b_I] or in general simply [b], provides the highest possible impedance in a frequency range of typical male phonation fundamental frequencies. This is expected, based on the fact that the vocal tract is completely sealed (occluded). Thus, a fully occluded condition may be regarded as the ideal impedance load except that phonation is possible for only a very short period of time. A lip trill is not far from this, although it allows the air to escape. The extension tubes seem to provide nearly the same high levels of impedance in the phonation frequency range but allow for sustained phonation. Similarly, the bilabial fricative [β:] also provides high impedance but not at the same level as the extension tubes. When the extension tube length is long enough to decrease F_1 below that of the closed tract F_1 (ie, for [b_I]), the level of positive reactance never exceeds that of the [b_I]. Thus, the optimum length of the tube would seem to be that which provides an F_1 equivalent to the closed tract resonance. In the example vocal tract used in this paper, such a tube length would be approximately 50 cm (see Figure 7).

What has not been answered is why an increase in impedance, specifically the positive reactance, is beneficial. From previous research it seems clear that vocal tract impedance can affect at least two levels of voice source function. The first level is an acoustic-aerodynamic interaction in which the acoustic pressures in the vocal tract affect the shape (amplitude and harmonic content) of the glottal flow pulse. At fundamental frequencies well below the first formant this generally has the effect of skewing the flow pulse so that the airflow is suppressed at glottal opening and maintained during the glottal closing phase. This produces the familiar "rightward" skewing of the flow pulse and ensures that significant energy is present in all harmonics. If the fundamental frequency is equal (or nearly) to the first vocal tract formant frequency the transglottal pressure (subglottal pressure – supraglottal pressure) will be exactly out of phase (180°) with the time-varying glottal area. This has the effect of suppressing the middle of the glottal flow pulse, giving a double-hump type of shape. Rothenberg[24] studied this effect and noted that the double-hump waveform [for the case of fundamental frequency (F_0) = first vowel formant frequency (F_1)] has a much lower average flow than for case of an F_0 that is not equal to F_1, while at the same time providing an harmonically rich voice source spectrum. Thus, phonating at a frequency at or near the first formant may allow for an efficient voice production that could possibly be associated with lower effort.

The second level of voice source function affected by vocal tract impedance is the mechanoacoustic interaction of the vocal tract pressures and the vibrating vocal folds. That is, the acoustic pressures in the vocal tract influence the vibrational characteristics of the vocal folds. Titze and Story[29] showed that increased vocal tract impedance (specifically the inertive component) lowered the phonation threshold pressure. *Phonation threshold pressure* is the subglottal pressure required to barely initiate and sustain phonation. Low values of threshold pressure suggest an ease of phonation as well as providing a greater range of available subglottal pressures with which to

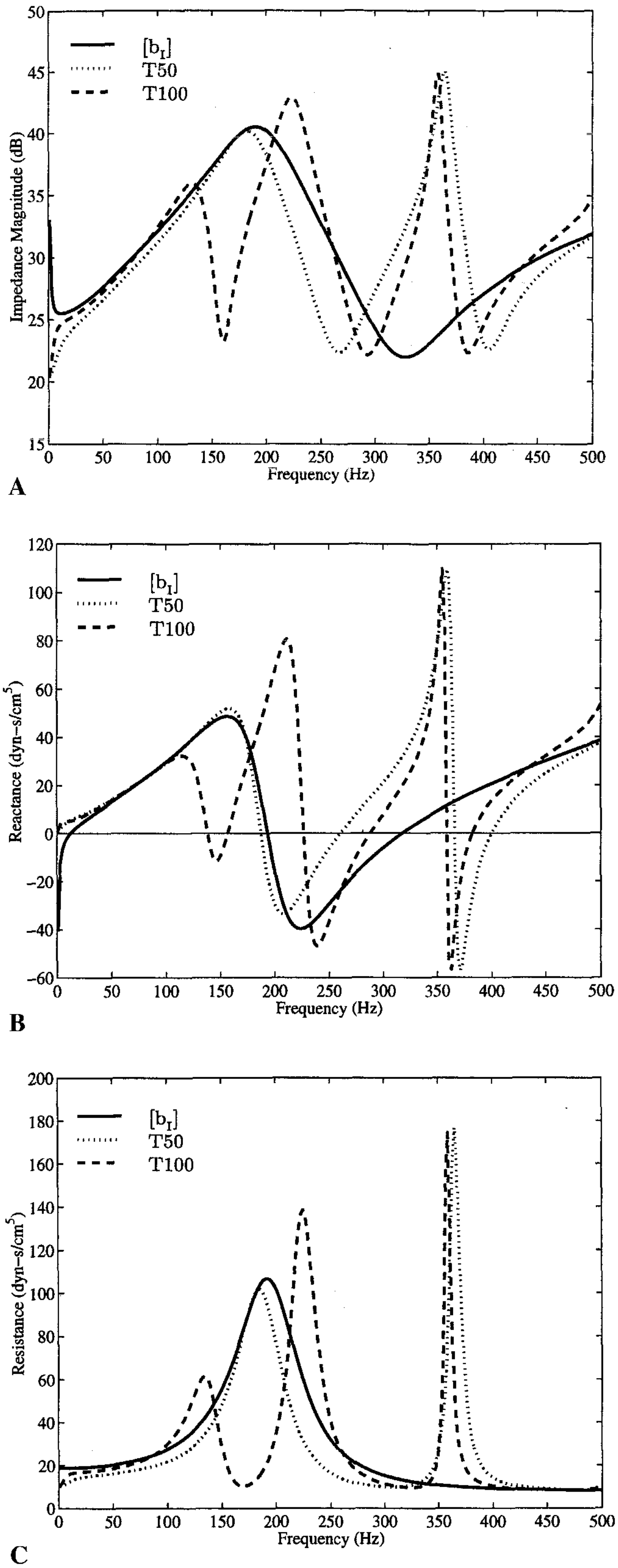

FIG. 7. Input impedance curves for the bilabial plosive $[b_I]$ (*solid line*) and for cases of two longer tubes [50 cm (*dotted line*) and 100 cm (*dashed line*)]; (**A**) Log magnitude of the impedance, (**B**) reactance, and (**C**) resistance.

produce phonation. (If phonation threshold pressure is high, much of the available range of subglottal pressure has been used just to initiate phonation.) Note that, unlike the present investigation, it was a constriction of the epilaryngeal tube (just above the glottis) in Titze and Story[29] that significantly increased the vocal tract impedance; typically this same constriction generates the singer's formant by forming a tube resonance near 3000 Hz.[34] However, it has also been shown, with low-dimensional vocal fold models, that high impedance can be detrimental to phonation, especially for control of F_0, when the fundamental frequency is at or near F_1[26]; these observations were also confirmed with a study of human subjects. In contrast, Sundberg[35] found that a soprano singer tended to tune the first formant frequency to the fundamental frequency of phonation. However, Sundberg[36] later showed that a loss of F_0 control occurred when a male subject attempted to tune F_0 to F_1 while phonating in modal register. This was not a problem when he phonated in falsetto nor was it a problem for two female subjects phonating at high pitches.

With regard to these studies, it should be pointed out that self-sustained oscillation of the vocal folds is often facilitated by positive reactance (inertance) but inhibited by negative reactance (compliance).[27] This means that phonating at an F_0 that is *exactly* equal to the first formant may not be advantageous because the reactance at this point is effectively zero (see Figure 4). Any slight increase of the F_0 would result in operating at a negative point on the reactance curve. This may inhibit vocal fold oscillation or force the vocal folds into a new vibrational pattern that is perhaps more weakly coupled to the vocal tract pressures; a change in vibrational pattern may also alter the F_0. However, phonation at an F_0 that coincides with the first positive peak of the reactance curve (Figure 4) could be advantageous since the inertance is high and the resistance (which includes radiation from the mouth) is higher than at a location far away from a formant (but not as high as at the formant frequency). The advantages will, of course, depend on the strength of the coupling between the voice source and the vocal tract pressures; a weakly coupled source may be only slightly affected by the input impedance while a strongly coupled source may experience large effects. The loss of F_0 control experienced by the male subjects in Sundberg's study[36] could be due to either an unfamiliarity of phonating near F_1 and staying on the positive portion of the reactance curve or that a male modal register is more susceptible to strong source-tract coupling than is a falsetto or high pitched female quality. This points to the likelihood of an optimal range of vocal tract impedance that depends on the mechanical properties of a particular vocalist's vocal folds and the type of phonation being produced (ie, modal, breathy, falsetto, etc).

There is also a third level of interaction between the vocal tract and vocal folds that is perhaps partly mechanical and partly neurological. In attempting to explain intrinsic vowel pitch (high vowels produce higher fundamental frequency than low vowels), a number of theories have been proposed that link nonlaryngeal articulatory movements with changes in laryngeal settings (see Sapir[37] for a summary). These may be purely passive biomechanical linkages, compensatory activation of laryngeal muscles, or a neural coupling of the articulatory and phonatory systems that induce reflexive changes in muscle activity. Thus, even though our study has shown that the extension tubes would be the most effective therapy based on acoustic considerations, other techniques such as the bilabial fricative may in fact be more effective when the mechanical and neural couplings are also included.

In summary, the benefit of using vocal tract extension tubes or partial occlusions may be to lower the first formant so that, theoretically, phonation fundamental frequency can be more easily produced near F_1. This would allow a student or patient to experience the sensory effects of lower phonation threshold pressure as well as a lowered average airflow (but still a harmonically rich voice source), both of which would be components of a low-effort voice production. We have not discussed the effect of vocal tract input impedance on the intensity and quality of sound radiated at the mouth (lip termination). While the voice-training techniques considered for this study would appear to decrease the sound level during their use, it is not clear what effect they will have on the sound level after training. A subject for future study is to determine how vocal tract impedance can be used to exercise the vocal folds for therapeutic and training purposes as well as to increase the sound pressure level and enhance vocal timbre.

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