Measurement of Mucosal Wave Propagation and Vertical Phase Difference in Vocal Fold Vibration

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MEASUREMENT OF MUCOSAL WAVE PROPAGATION AND VERTICAL PHASE DIFFERENCE IN VOCAL FOLD VIBRATION

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Examination of the surface wave properties of the vocal fold mucosa is becoming an important part of assessment of vocal function. A key wave property is propagation velocity, which determines the phase delay between the upper and lower margins of the vocal folds. Excised canine larynges were used to measure this phase delay, and therewith propagation velocity. The motion of two flesh points was tracked stroboscopically. Differential displacements between the flesh points were matched to displacements of a model. A least-squared fit of the data to the model provided the numeric values of propagation velocity, which varied from 0.5 m/s to about 2.0 m/s, depending on fundamental frequency. The corresponding phase delay along the medial surface of the vocal folds varied from about 60°/mm to 30°/mm.

KEY WORDS — glottis, mucosal wave, vocal fold vibration, voice.

INTRODUCTION

It is now well established that self-oscillation of the vocal folds is facilitated by a phase delay in movement of the upper margin of the folds with respect to the lower margin. Ishizaka and Matsudaira[1] demonstrated this by deriving analytic expressions for conditions of oscillation with a two-mass model of the vocal folds. Subsequently, Titze[2] confirmed the derivation by modeling a surface wave that propagated vertically along the medial surface of the vocal fold mucosa. A finite propagation velocity of the mucosal wave supplies the phase delay, and thus the two approaches have merged conceptually into one theory of vocal fold vibration. The theory is based on small-amplitude assumptions, with flow-induced vibration being sustained around a small glottal opening.

More recently, the clinical importance of the mucosal wave has been described by Bless et al.[3] Patients with vocal fold lesions and scarred tissue in the mucosa show a reduced amplitude of the mucosal wave. Furthermore, the phonation threshold pressure (the minimum lung pressure required to establish phonation at a given pitch) has been shown to be related to the mucosal wave velocity,[4,5] suggesting that "ease of phonation" is facilitated by a greater phase delay.

Given these theoretic and clinical observations, it seems logical to conduct an investigation to measure the phase delay and the associated mucosal wave velocity. In particular, it is important to know how these quantities vary with the fundamental frequency (F_0). This would then allow better interpretation of phonation threshold pressure, which is known to vary nonlinearly with the F_0.[4] One criterion for successful phonosurgery might be the lowering of phonation threshold pressure,[6] which expands the range of intensity that can be achieved in phonation.

Relations Between Mucosal Wave Velocity and Vertical Phase Delay. Hiroto[7] was one of the first to point out that the maximum glottal width, as seen from above, depends on time-delayed movements between the upper and lower margins of the vocal folds. More recently, Hanson et al[8] and Berke et al[9] confirmed this finding with glottographic measurements conducted on human subjects and canine in vivo preparations, respectively. It is understood that glottal width is a time- and space-dependent function that varies in both the anterior-posterior direction and the inferior-superior direction. It can be identified at two vertically separated flesh points on the medial surface of the folds, as shown in Fig 1A. At these points, the time variation of the glottis is modeled as

$$g_1(t) = \mathrm{Max}[0, g_{01} + 2a_1 \sin(2\pi F_0 t)] \quad (1)$$

and

$$g_2(t) = \mathrm{Max}[0, g_{02} + 2a_2 \sin(2\pi F_0 t - \phi)] \quad (2)$$

where the subscript 1 refers to the lower flesh point and subscript 2 to the upper flesh point. The quantities g_{01} and g_{02} are prephonatory glottal widths, a_1 and

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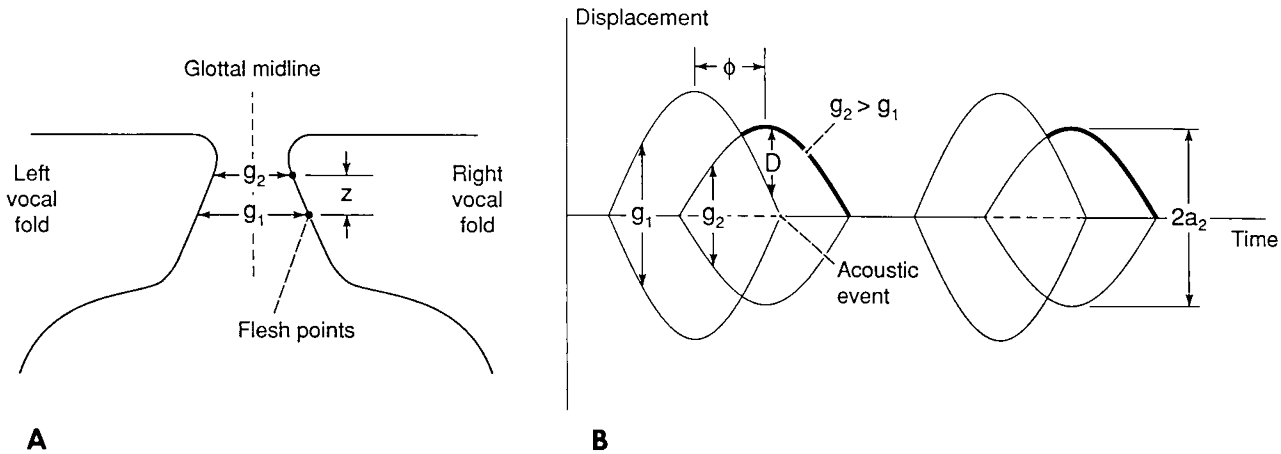

Fig 1. Illustration of movement of flesh points on upper and lower margins of vocal folds. A) Frontal section through vocal folds. B) Displacement versus time for glottal width. Heavy lines illustrate portions of cycle over which measurements can be made. See text for explanation of other symbols.

a_2 are the amplitudes of (assumed) sinusoidal flesh point motions in the medial-lateral direction, and ϕ is the vertical phase delay. An assumption of symmetry between left and right vocal fold movements is implied in the equations, as indicated by the factor of 2 in front of the amplitudes of vibration. Time variations $g_1(t)$ and $g_2(t)$ are shown in Fig 1B for two cycles of vibration. (Some features of this Figure will be explained later.)

It should be kept in mind that the specific glottal widths $g_1(t)$ and $g_2(t)$ are defined only for one common anterior-posterior position. A more complete model of static and dynamic glottal shapes, involving variations along the length of the vocal folds, has been proposed,[10] but this additional complexity is not needed for the present study.

Assuming a surface wave to be propagating vertically upward in the mucosa with a velocity c, the time delay between the two flesh points separated by a vertical distance z is

(3) $$\tau = z/c$$

and the corresponding phase delay is this time delay normalized to the fundamental period of vibration T,

(4) $$\phi = 2\pi\tau/T = 2\pi F_0\tau = 2\pi F_0 z/c$$

If we know the flesh point separation z (Fig 1A) and the fundamental frequency F_0, a measurement of the phase angle ϕ will reveal the propagation velocity c of the mucosal wave. The experimental procedure for obtaining these measures will now be described.

MATERIALS AND METHODS

Excised canine larynges were harvested from mongrel dogs (body weights 20 to 23 kg). The dogs had been killed painlessly in a cardiovascular research laboratory. Only grossly normal larynges were used in this study. From approximately 10 larynges that were harvested, 5 were judged normal and kept for experimentation. Rejection was based on insufficient size, evidence of disease, or obvious asymmetries across the midline.

Techniques for dissecting, mounting, and controlling the glottal configuration of the larynx are described elsewhere.[11] Pressurized air with controlled temperature and humidity was used to induce self-oscillation of the vocal folds, as described by Baer,[12] Durham et al,[11] Cooper,[13] and Yanagi et al.[14]

A custom-designed triggering circuit was used to phase-lock the flashes of a stroboscopic light source (Pioneer DS 330-ST) to specific events in the period of vibration. The stroboscopic image of the top view of the folds, which filled the entire screen of a 19-in video monitor, could thus be frozen to make measurements (in screen coordinates) of glottal dimensions at any given phase in the cycle. Magnification was 10:1, based on an object-lens distance of 45 cm (Sony DXC-102 video camera with a 90-mm microlens).

Prior to mounting the larynx, we placed two small suture marks at the middle of the membranous vocal folds using 9-0 nylon stitches. One mark was at the upper margin and the other approximately 2 mm lower. The vertical distance between these two marks was measured with a micrometer (0.1-mm accuracy) and constituted the distance z in Fig 1A and in equations 3 and 4.

Different subglottal pressures and different elongations of the vocal folds were used to obtain different F_0 values. The two audio channels of a high-fidelity video cassette recorder were used to record two time-locked acoustic signals alongside the stroboscopic video image. One acoustic signal was the audio signal from a microphone (Realistic 33-1056A)

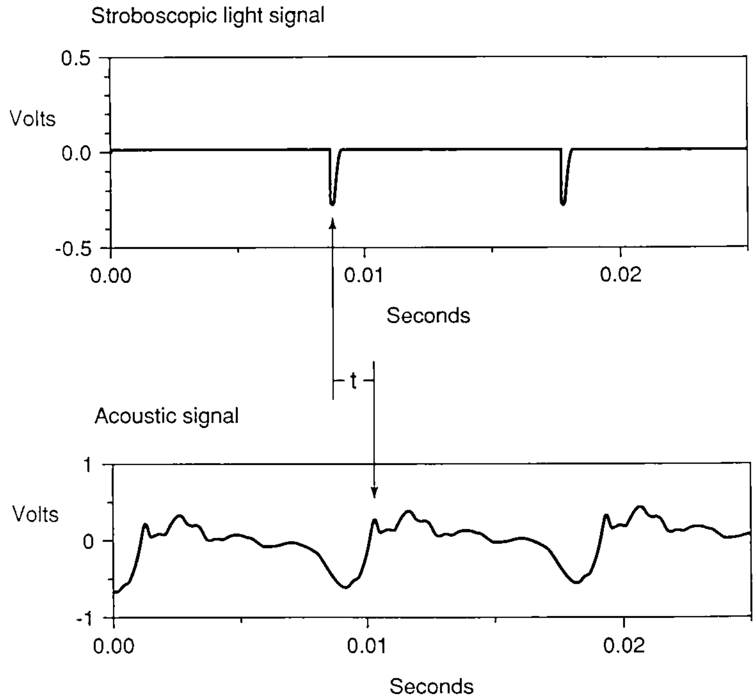

Fig 2. Display of simultaneously recorded strobe flash signal (upper trace) and microphone signal (lower trace). Time interval (t) is relative time between two identifiable events in cycle.

placed 5 cm from the vocal folds, and the second signal was a timing signal obtained from a light sensor that converted the stroboscopic flashes into electrical signals. In this manner, video events could be correlated with a constant acoustic event in the vibratory cycle. Figure 2 shows an example of the two time-locked audio signals. The interval t defines the time between the strobe flash (top trace) and the initial burst of acoustic pressure and glottal closure (bottom trace). The burst of acoustic pressure was taken to be the constant reference event, also shown in Fig 1B. Phase differences between flesh point movements could then be determined relative to this reference event and relative to each other.

Data Reduction. During video playback, the lateral displacement D between the two marks was measured for each of a number of phases. According to equations 1 and 2, this displacement is

$$(5) \quad D = g_2 - g_1 = (g_{02} - g_{01}) + 2a_2\sin(2\pi F_0 t - \phi) - 2a_1\sin(2\pi F_0 t)$$

The quantity D and the phase angle ϕ are shown in Fig 1B. Only those phases in which g_2 was greater than g_1 could be used for measurement (thick portion of g_2), because in all other cases the upper mark

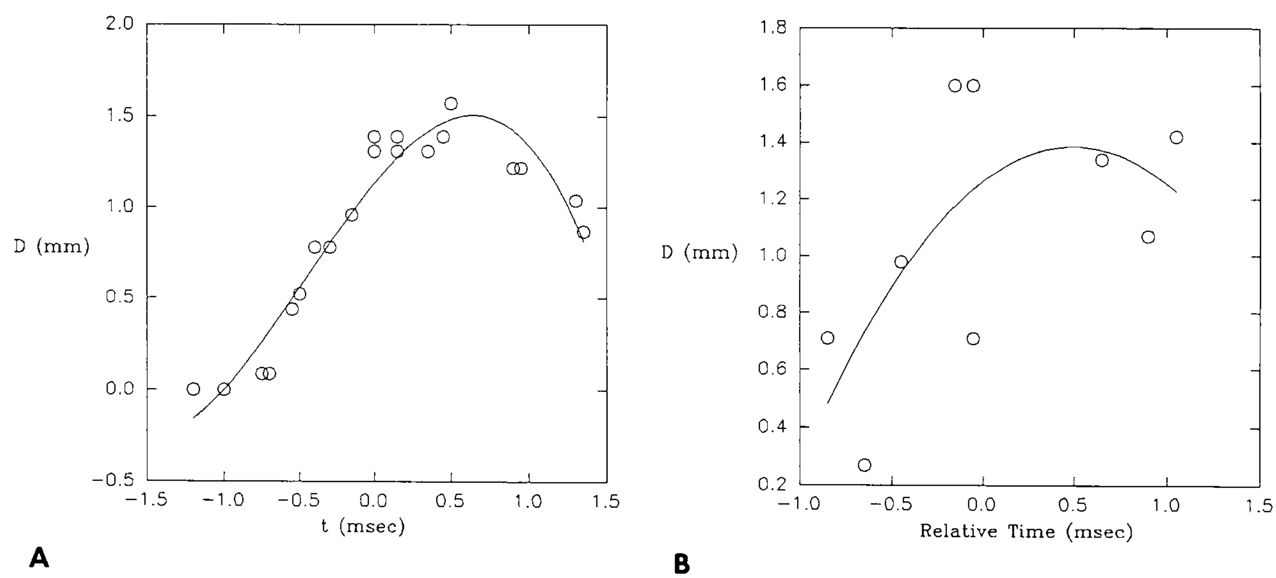

Fig 3. Distance (D) between two marks on vocal folds as function of relative time (t) for A) best case and B) worst case. Solid curve is model given by equation 5.

MUCOSAL WAVE VELOCITY AND CORRESPONDING PHASE DELAY

Larynx No.	F_0 *(Hz)*	*Velocity c (m/s)*	*Phase delay φ/z (°/mm)*
1	95	0.587	58.3
	107	0.877	43.9
	114	0.673	61.0
	119	0.704	60.9
	123	0.858	51.6
	131	0.778	60.6
	134	0.817	59.1
	140	0.847	59.5
	157	0.946	59.8
	173	1.466	42.5
2	129	0.866	53.6
	136	0.934	52.4
	154	1.047	53.0
	163	1.124	52.2
	178	1.139	56.3
3	126	0.859	52.8
	141	0.940	54.0
	158	1.063	53.5
	163	1.086	54.1
	181	2.081	31.1
4	127	1.012	45.2
	134	1.147	42.1
	139	1.254	39.9
	148	2.177	24.5
5	137	0.951	51.8
	148	1.469	36.3
	152	1.764	31.0
	155	2.001	27.0

F_0 — fundamental frequency, φ — phase angle, z — flesh point separation.

shadowed the lower mark. Given that the glottis is closed over about half of the period, and given that over about one quarter of the period the bottom mark is shadowed, the average measurement period was only about one quarter of a cycle (duration of thick line).

The acoustic signals from audio playback were displayed on a digital oscilloscope (Data 6000). The stroboscopic reference time t was measured along with each value of D. More than 10 sets of D versus t data could be obtained for each pitch of a given larynx. To determine additional unknown factors in equation 5, the maximal glottal width at the upper flesh point ($2a_2$, shown in Fig 1B) was also measured separately on the video screen. Finally, the quantity $g_{02} - g_{01}$ was determined to be negligible, because the marks were only about 1.5 to 2.0 mm apart and the prephonatory glottis was nearly rectangular. This left only a_1 and φ as unknowns.

Using nonlinear regression curve fitting (Marquardt-Levenberg algorithm in Sigmaplot 4.0 program), we fitted the data to equation 5, where a_1 and φ were parameters to be optimized under program control. The criterion for optimization was the combined least-squared difference between the measured and calculated Ds for the 10 or more data points.

Examples of best-case and worst-case matches between the measurement and the model of D as a function of t are given in Fig 3. In the best case (Fig 3A), a sinusoidal difference function for D can readily be seen, both for the data and the model. (The difference between two sinusoids of different phase and different amplitude is also a sinusoid.) In the worst case (Fig 3B), the sinusoidal nature of the data was obscured, but the model was nevertheless deemed appropriate. Note that the curves follow the pattern one would predict from Fig 1B. The difference function D is at a maximum near $t = 0$, the acoustic reference event, and diminishes in both directions on the thick line.

RESULTS

The Table shows data of mucosal wave velocity c and phase delay per millimeter (φ/z) from five excised canine larynges. At least four different F_0 values were obtained on each larynx. The columns of data are related by the equation

$$\phi/z = 360F_0/c \qquad (6)$$

which is equation 4 expressed in degrees rather than radians. Note that the velocities range from about 0.6 m/s to about 2.2 m/s, with higher values consistently corresponding to higher F_0 values. The phase delay per millimeter decreases with F_0.

Figure 4 shows the data of the Table graphically. Except for larynx 5, which shows an unusually steep rise of c with F_0 (and a correspondingly steep fall of φ/z), the results suggest that wave velocity in the mucosa may increase linearly with F_0. A threefold increase in c, from 0.5 m/s to 1.5 m/s, is observed over the 100- to 180-Hz range. If larynx 5 were excluded., the increase would still be more than twofold. Phase delay may decrease linearly, but at a relatively moderate rate of decline (less than 30% over the 100- to 180-Hz range, and less if larynx 5 is excluded).

The rate of decline of φ/z with F_0 may actually be overestimated. As the vocal folds are elongated, they usually shrink in thickness to preserve overall tissue volume. A 30% elongation, for example, would decrease the separation z of the marks by 30%. This would then keep φ/z nearly constant with F_0, and c would increase in proportion to F_0. Further investi-

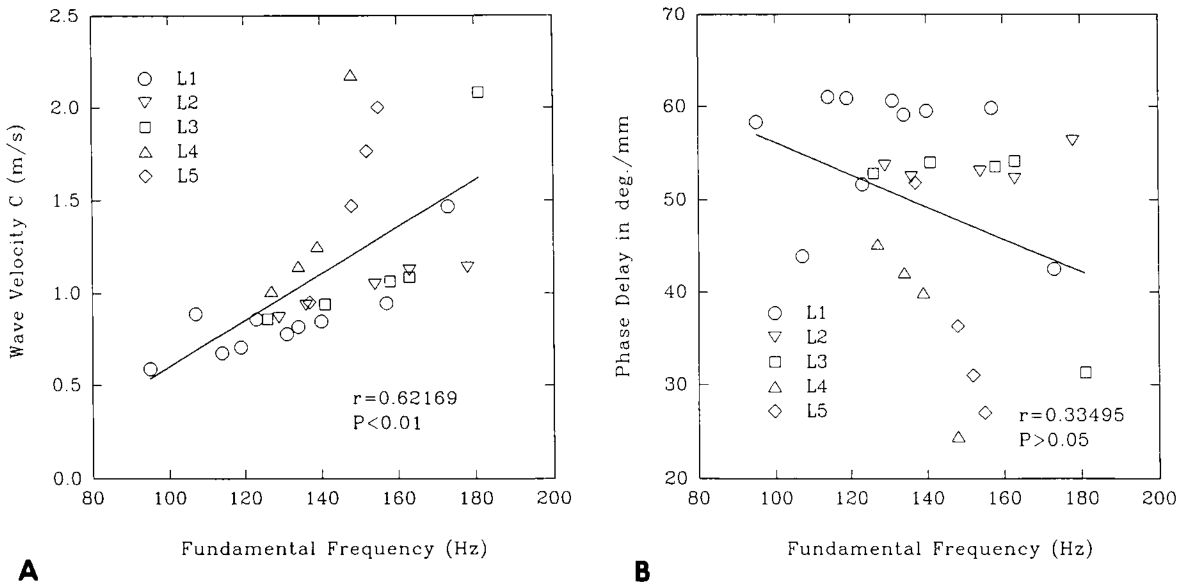

Fig 4. Data from Table, shown graphically. A) Wave velocity c versus fundamental frequency for all five larynges. B) Phase delay in degrees per millimeter as function of fundamental frequency for all five larynges.

gation of this effect is needed.

DISCUSSION AND CONCLUSIONS

In experiments conducted on excised canine larynges, Baer summarized his findings with respect to mucosal wave velocity as follows.

> The derived propagation velocities are on the order of 1.0 m/s. This value may be compared with the value of 1.6 m/s reported by van [*sic*] Gierke et al (1952) on human skin and in such places as the thigh or forearm. As discussed earlier, however, wave velocity on the more lateral parts of the superior surface drops to 0.3 to 0.5 ms, perhaps because the membranes are more slack or because the effective thickness is greater.[12(p190)]

The article by Von Gierke et al[15] is also worthy of note. It is often quoted as an authoritative reference on human skin vibration.

It is clear from Fig 4A that Baer's value 1.0 m/s is in the center of the range measured here. Our findings, therefore, agree with his. Slower wave velocities (0.1 to 0.5 m/s) were measured by Hirano et al[16] on the superior surface. These findings do not conflict with our results in light of Baer's comment that mucosal waves slow down considerably as they propagate laterally. It is important, therefore, to specify where the wave velocity is measured. Hirano et al did this carefully in their study.

The importance of quantifying the mucosal wave velocity on the medial surface stems from the fact that phonation threshold pressure, the minimum pressure required to establish phonation, depends critically on this propagation velocity.[2] Thus, by knowing how c varies with F_0 on this surface, a better understanding of phonation threshold pressure may emerge in the future. Direct or indirect estimates of this pressure may then lead to better tools for assessment of normal and abnormal vocal function.

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