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MEASUREMENT OF YOUNG'S MODULUS IN THE IN VIVO HUMAN VOCAL FOLDS

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Currently, surgeons have no objective means to evaluate and optimize results of phonosurgery intraoperatively. Instead, they usually judge the vocal folds subjectively by visual inspection or by listening to the voice. This paper describes a new device that measures Young's (elastic) modulus values for the human vocal fold intraoperatively. Physiologically, the modulus of the vocal fold may be important in determining the nature of vocal fold vibration in normal and pathologic states. This study also reports the effect of recurrent laryngeal nerve stimulation on Young's modulus of the human vocal folds, measured by means of transcutaneous nerve stimulation techniques. Young's modulus increased with increases in current stimulation to the recurrent laryngeal nerve. Ultimately, Young's modulus values may assist surgeons in optimizing the results of various phonosurgeries.

KEY WORDS — elastic modulus, phonosurgery, vocal fold, Young's modulus.

INTRODUCTION

This paper describes a new device that measures Young's (elastic) modulus intraoperatively in the in vivo human vocal folds. Elastic modulus values may provide surgeons with an objective means of evaluating phonation intraoperatively, and therefore may be useful for guiding and optimizing results of phonosurgery. Traditionally, surgeons have gauged changes made to the vocal folds by visual inspection or by listening to the patient's voice. These judgments are purely subjective, and as a result surgical outcomes are often unpredictable. Because poor outcomes most often result from misjudgment of the appropriate amount of augmentation or medialization of the vocal folds, resulting in abnormal stiffening of the vocal folds, an objective procedure for evaluating vocal fold stiffness intraoperatively might improve the success rate for such surgeries, and would have broad application over a wide range of phonosurgical procedures.

Young's (elastic) modulus accurately represents the tissue elastic properties,[1] and was therefore chosen as a measurement standard. Young's modulus is calculated from the following equation: Young's modulus = Stress/Strain, where Stress is defined as force required for lateral movement, divided by tissue contact area over which the force is applied; and Strain is defined as change in length of x at a particular x, or amount of displacement. An alternate formulation for differential Young's modulus is ΔYoung's modulus = ΔStress/Strain, where ΔStress is differential stress, or the change in force divided by the tissue contact area over which the force is applied. This modulus measures both the physiologic and dynamic aspects of vocal fold compliance to variations in force and stimulation, and thus is probably a superior measure of fold properties[2] (also K. S. Stevens, unpublished observations).

Physiologically, the elastic modulus of the vocal fold tissue may be a prime determinant of the wave motion of the mucosal membrane.[3-6] The mucosal wave travels from the inferior portion of the folds to the superior, and then moves laterally onto their surface. This process transforms the egressing airstream through vocal fold vibration during phonation. The periodic interruption in airflow in turn produces the acoustic signal that is perceived as voice.[7] Hence, the elasticity of the vocal fold tissue is a key factor in the control of phonation.[8,9]

Anatomically, the layers of the vocal folds exhibit different mechanical properties.[10] Hirano[11] described these properties in the body-cover theory of vocal fold vibration. He described the vocal fold as a 2-layer system: a muscular layer (body) and a nonmuscular layer (cover). The cover consists of squamous epithelium and intermediate layers of loose connective tissue (lamina propria). It is very pliable, but has no intrinsic contractile property. The body includes the deep layer of the lamina propria and the vocalis muscle, whose contraction stiffens the body. These properties may contribute to the formation and characteristics of the traveling wave and the resulting

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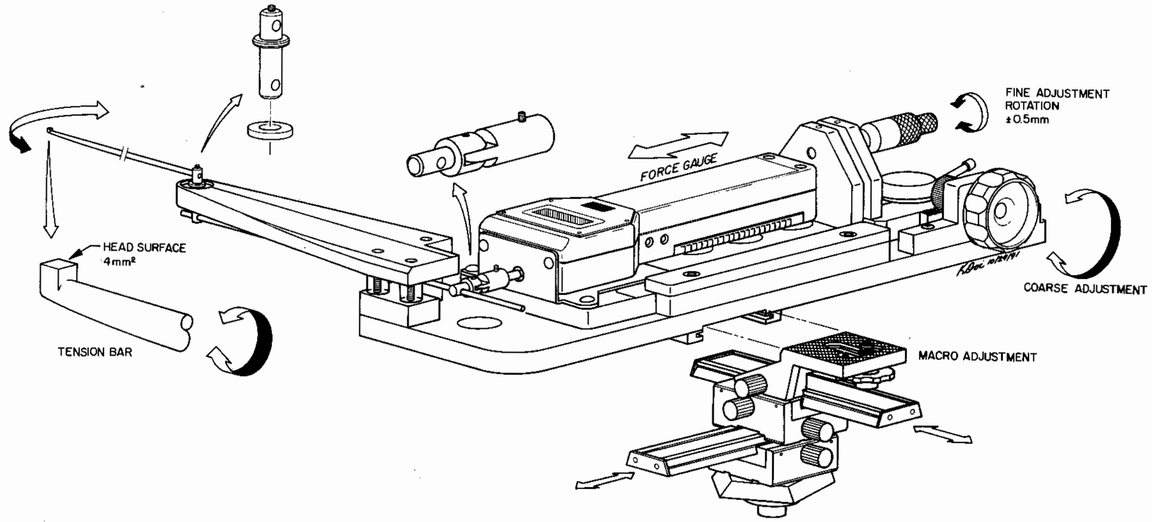

Fig 1. Diagram of new device for measuring differential Young's (elastic) modulus.

vocal qualities that can be produced.

Since the cover assumes most of the vibration near its surface,[12] an understanding of its elastic properties is of primary importance. Intuitively, it would seem that the combined stiffness of the entire vocal fold would be determined by the extrinsic longitudinal tension of the cover and the internal stiffening of the body. Thus, the elastic properties of both layers influence the vibration of the vocal folds.[13]

In vivo elastic modulus values have not been reported previously. However, a number of authors have measured in vitro elastic modulus values in order to predict the in vivo state of vocal fold vibration. Ishizaka and Kaneko[14] fastened a thread to a freshly cut human vocal fold, and then stretched the cord laterally to measure the displacement and force applied. From this preparation, they estimated the stiffness constant K at 3.7×10^4 dynes/cm. Kakita et al[2] investigated the mechanical properties of vocal fold tissues and reported ranges and orders of magnitude for Young's moduli and shear moduli of different layers of canine vocal folds. Weights were hung on the tissue samples, and the resulting elongation was measured with a microscope. Although their results provided some of the first quantitative estimates of the elastic moduli, methodological problems (including undefined reference length and questionable viability of the tissue) limit the generality of their measurements.

Perlman et al[15,16] investigated the in vitro elastic moduli of canine vocal fold tissues in viable condition. Longitudinal stepwise elongation was applied to the vocal folds, and the force was measured. From the force elongation curves and stress-strain curves of the vocal fold tissue, a secant Young's modulus for the body and cover was obtained. The longitudinal secant Young's modulus, defined as the ratio of total stress to the total increase in strain from a reference length, ranged from 1.0×10^6 dynes/cm^2 at 10% strain to 4.0×10^6 dynes/cm^2 at 50% strain.

Recently, Alipour-Haghighi and Titze[17] measured the in vitro longitudinal elastic modulus of canine vocal folds that were kept viable in Krebs solution. They used a slow cyclic stretch-and-release technique to measure the stress-strain in the range of 0% to 40% elongation over an approximate in situ length. These stress-strain data, which apply to longitudinal vocal fold tension, were modeled with polynomial and exponential functions. Alipour-Haghighi and Titze proposed that the elastic properties of the vocal fold tissues are nonlinear for both body and cover over most of the strain range, but that linear approximations can be made at low strain (strain < 15%). At these low strains, the cover has about twice the stiffness of the body as estimated with the longitudinal Young's modulus. Such low strain values are of interest, since they represent most normal phonation.[18]

Although no in vivo modulus measures have been reported, associated measures of vocal fold function made intraoperatively have been described. Fukuda et al[19] developed a technique in which an external vibrator was used to create a wave motion in the vocal folds. This motion was evaluated intraoperatively for symmetry by stroboscopy. However, the relationship between externally induced and natural vocal fold vibration is unclear. LeJeune[20] designed a device to measure the degree of vocal ligament tightening during laryngeal framework surgery. However, his device measured only strain, not stress. Further, strain was determined by pinching the vocal fold, possibly injuring the tissue. Berke et al[21] intraopera-

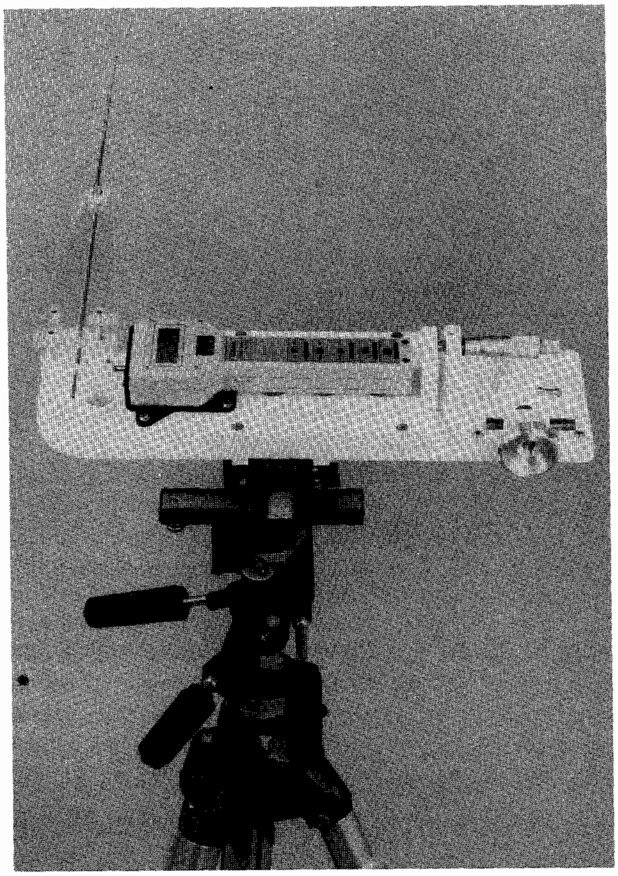

Fig 2. Photograph of actual device for measuring differential Young's (elastic) modulus.

tively monitored human vocal fold vibration by insufflating air rostrally through the vocal folds while manually adducting the arytenoids. This technique was used intraoperatively to monitor fold function and determine the end point for injecting Teflon into the vocal folds of a patient with previous failed attempts. However, the technique is imprecise and indirect compared to the direct stimulation of the laryngeal muscles.

The device described below is designed to overcome the limitations of previous methods by permitting measurement of vocal fold function in vivo. The device is described in detail below, along with its use in patients. We also report measurements of the activated muscular transverse elastic modulus.

METHODS

Device Construction. The device constructed to measure the Young's modulus of the in vivo human vocal folds is shown in Figs 1 and 2. This device was designed to meet several criteria. First, it moves into position easily and rapidly during phonosurgery, so that the elastic modulus can be measured quickly and easily. The device's deflection bar occupies very little space within the introitus of the larynx, and does not interfere with the surgical manipulation of the vocal fold. This allows dynamic measurement of the elastic modulus throughout a phonosurgical procedure.

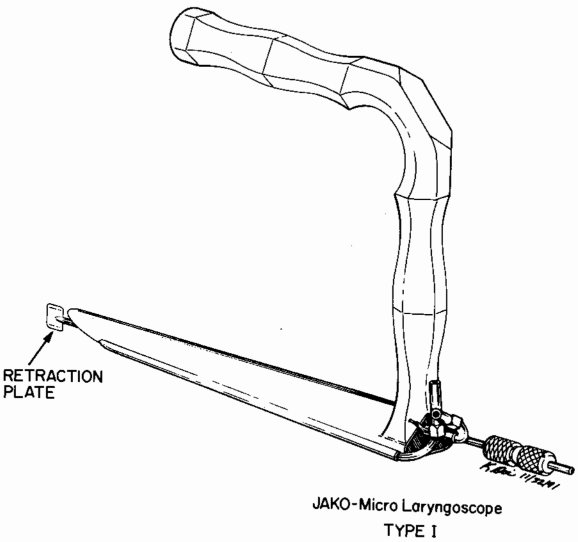

Fig 3. Diagram of modified Jako laryngoscope.

Second, the device measures the vocal fold's elastic modulus rapidly by deflecting the vocal fold a small distance, with measured force applied to a small area of the fold. Rapid measurement minimizes the effect of strain "creep" and stress "relaxation" in vocal fold tissue.[2] If uncontrolled, these factors will distort Young's modulus values and result in inaccurate measurements of the elasticity of the tissue. In our preliminary elastic modulus studies, stress "relaxation" was observed when force was applied to the tissue for longer than 30 seconds.

Third, the device is sensitive to very small changes in the modulus. The device incorporates a Shimpo Digital Force gauge (Shimpo force gauge DF-0.5R, Shimpo American Corp), which combines a light beam detection design with a microcomputer for measurement of push-pull forces. This gauge can measure forces from any angle and has a resolution of 0.1 g. This enables the device to record a change in Young's modulus of as little as 2,500 dynes/cm^2 per 0.2 mm of displacement. The computer interface ensures data can be processed and evaluated statistically during surgery.

This force gauge was placed on a lightweight platform that permits frictionless movement of the gauge during the measurement process. To facilitate the device's maneuverability and precise movement within the glottic area, coarse, intermediate, and micrometer adjustments are possible (Fig 1). The micrometer tuning adjustment produces precise, small

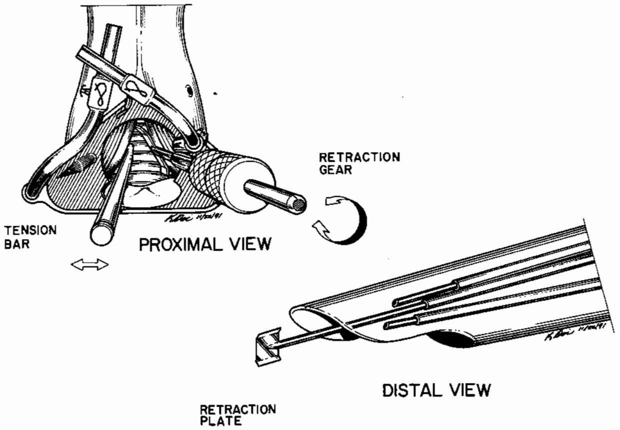

Fig 4. Placement of modified Jako laryngoscope within glottic area, showing footplate on stimulated vocal fold and retraction plate on nonstimulated vocal fold.

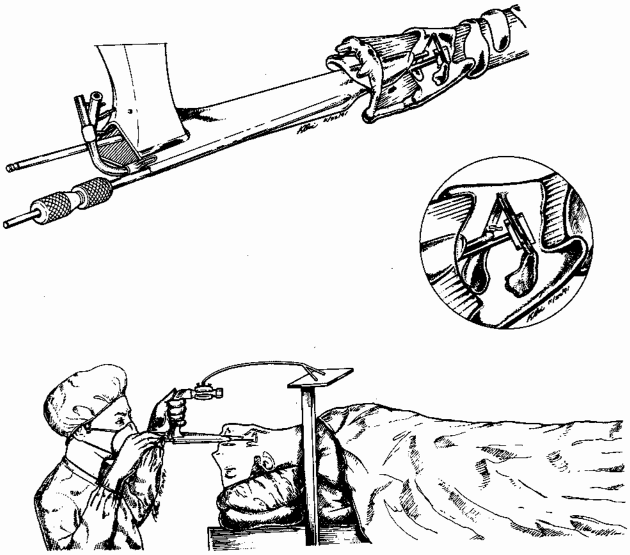

Fig 5. Diagram of modified Jako laryngoscope during its suspension and stabilization of glottis.

movements (as little as 0.1 mm) of the tissue contact footplate.

The deflection bar pivots at its midsection, so that any deflection or force exerted on the footplate by the stimulated vocal fold will result in an equal displacement or force on the gauge. A mechanical linkage between the deflection bar and the gauge facilitates smooth transmission of force, and also minimizes loss of force from the footplate to the gauge.

Measurement Procedure. Figures 3 and 4 show a Jako direct laryngoscope, which was modified for this study by incorporating a small retraction plate with a long handlebar within the laryngoscope. This plate is used to retract the nonstimulated vocal fold away from the deflection footplate. This prevents the nonstimulated vocal fold from touching the deflection footplate or bar. Any contact between the nonstimulated vocal fold and the device results in mismeasurement of the elastic modulus.

The modified Jako laryngoscope was suspended during the measurement (Fig 5). Use of a suspension laryngoscope stabilizes the thyroid cartilage and prevents unnecessary movement of the larynx. Pilot studies have shown that laryngeal movement interferes with elastic modulus measurement.

A small footplate is located at the end of the deflection bar. This plate has a surface contact area of 0.04 cm^2, and is placed posterior to the midsection of the vocal folds (Figs 4 and 5). This location reflects the greatest lateral excursion of the vocal folds during phonation, and thus is most representative of the fold's elastic property.[22] As the recurrent laryngeal nerve is electrically stimulated with a constant current, the affected vocal fold deflects the footplate medially and exerts a force on the force gauge.

At the beginning of each measurement, the device must be initialized by using the intermediate and micrometer tunings to adjust the footplate, so that the force exerted on the footplate by the vocal fold is zero. The resulting position of the footplate at zero force is defined as the initial zero displacement.

In Vivo Human Study. Five men volunteered for this study. They ranged in age from 40 to 50. Four of the 5 subjects had no history of laryngeal lesions or voice problems, and preoperative indirect laryngoscopy and thorough head and neck examination revealed no current laryngeal or voice disorder. One subject had evidence of a hyperfunctional voice disorder, characterized by a moderately rough voice and no laryngeal lesion.

After appropriate research protocol consents were obtained, the subjects were brought to the operating room and placed supine on the operating table. Five milliliters of 1% Xylocaine was used to infiltrate the sensory branch of both superior laryngeal nerves to suppress potential laryngospasm. A slow mask ventilation with 3.5% isoflurane–nitrous oxide and 100% oxygen supplement was used until the subject's depth of anesthesia was maximized. Subsequently, the subject underwent orotracheal intubation with an endotracheal tube (No. 5). Thereafter, 2% isoflurane gas was used to maintain anesthesia during the measurement process. No paralytic agent was used during the study.

The subject's neck was gently hyperextended, draped, and prepared for transcutaneous recurrent laryngeal nerve stimulation. This technique has been described previously and used relatively safely in humans.[23] Two monopolar Teflon-coated needles were inserted through the skin. One was inserted

TABLE 1. MEASURED YOUNG'S MODULUS VALUES FOR THREE STIMULATION LEVELS

	Rest	*High Stimulation*	*Low Stimulation*
Mean	126,616	215,894	191,688
SD	76,349	11,432	111,854
Minimum	24,500	58,800	41,650
Maximum	294,000	441,000	416,500

Data are dynes per square centimeter.

down to the level of the posterior aspect of the left cricoid cartilage, and 1 was inserted along the left tracheoesophageal groove inferior to the cricoid cartilage. These needles conducted various currents from a nerve stimulator (model S2LH, WR Medical Electronics Co, St Paul, Minn) to stimulate the left recurrent laryngeal nerve. The nerve was transcutaneously stimulated at 80 Hz, with 2 different currents (3.8 mA and 3.2 mA); pulse duration was 1.5 milliseconds.

All measurements were made in the subject's left vocal fold. Three separate measurements of the elastic modulus were made: in the fold's resting state; at a high stimulation level, at which point the left vocal fold adducted to midline with prominent vocalis bulging (3.8 mA); and at a lower stimulation level (3.2 mA).

All subjects received 3 blocks of trials (1 per stimulation condition). The resting condition was always first, followed by the high stimulation condition and then the low stimulation condition. A rest period of 3 to 5 minutes separated adjacent stimulation conditions to reduce possible effects of vocalis muscle fatigue. Our previous experience with the in vivo canine model indicates that this period is sufficient.

Within each condition, 2 complete measurement cycles were made in rapid succession. At the beginning of the experiment, the footplate was placed posterior to the midsection of the vocal fold, and initialized as described above. The footplate remained in contact with the vocal fold until the entire experiment was completed. The appropriate stimulation was applied, displacement was increased in 0.5-mm steps from 0 to 3.0 mm, and force was measured for each displacement level. The device was then reset to zero, and the sequence of measurement was repeated. The 2 sets of measurements within a condition lasted less than 25 seconds.

At each increment, the vocal fold exerted different forces on the footplate. These forces reflect the inherent elastic property of the tissue at that given tissue displacement (stretch). Force values were recorded and processed by the computer to derive values of Young's modulus as follows. First, the measured mass at each displacement level was multiplied by the constant 980 cm/s^2 to derive force (mass multiplied by acceleration). Stress was then calculated by dividing the force at each displacement by the area of the footplate (0.04 cm^2). Next, differential stress (ΔStress) was calculated by using the formula $(F - F_o)/A$, where F is force at the current displacement, F_o is force at the previous displacement, and A is the area of the footplate. Similarly, strain was calculated as $(x - x_i)/x_i$, where x is the current displacement and x_i is the previous displacement. The differential Young's modulus is the ratio of differential stress to strain, or ΔStress divided by Strain.

RESULTS

To determine how well in vivo measurements of Young's modulus could be reproduced, we examined the correlation between the first and second measurements at each displacement and stimulation level, for the group as a whole and within each subject. The different stimulation conditions were combined for this analysis. For the group as a whole, Pearson's r was .84; values for individual subjects ranged from .97 to .79 (all correlations significant at $p < .05$). These values indicate very good measurement replicability, and suggest that the device may be used reliably to measure vocal fold elasticity in vivo.

Table 1 gives the mean, standard deviation, and ranges of Young's modulus values for the 3 stimulation conditions. Measurements are in dynes per square centimeter. A 2-way (stimulation condition by subject) analysis of variance using the differential Young's modulus as the dependent variable showed significant differences among stimulation conditions ($F_{2,135} = 9.42$, $p < .05$), no significant differences between subjects ($F_{4,135} = 0.09$, $p > .05$), and no significant interaction between subjects and conditions ($F_{8,135} = 0.08$, $p > .05$). Post-hoc Scheffé comparisons showed that the resting condition differed significantly from high stimulation ($p < .01$) and from low stimulation ($p < .01$); the high and low stimulation conditions did not differ significantly from one another ($p = .53$).

Figure 6 shows the relationship between the differential Young's modulus and vocal fold displacement. Young's modulus increased in a linear fashion with displacement, for all stimulation conditions (for the resting state, $F_{1,53} = 532.12$, $p < .05$, $r^2 = .91$; for high stimulation, $F_{1,53} = 295.00$, $p < .05$, $r^2 = .85$; and for low stimulation, $F_{1,53} = 166.56$, $p < .05$, $r^2 = .76$).

DISCUSSION

Our results demonstrate that the new device pro-

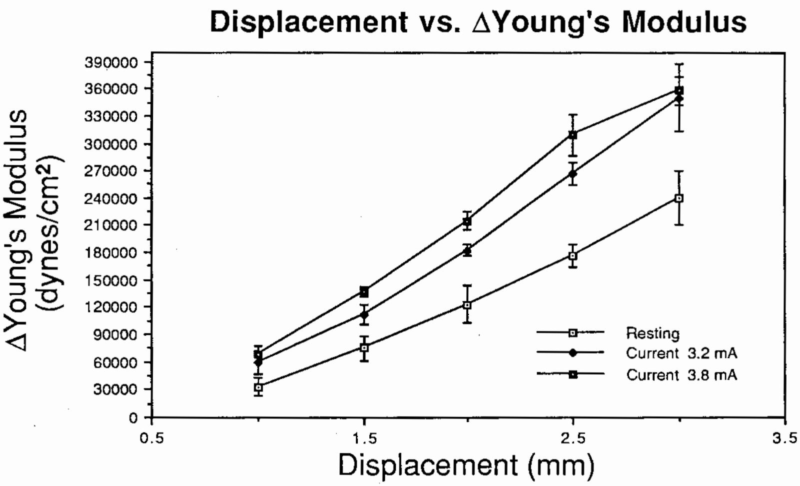

Fig 6. Graph of vocal fold displacement versus differential Young's modulus.

duces reliable in vivo measurements of the differential Young's modulus. The measurements did not differ significantly among speakers, suggesting that similar stimulation conditions will result in comparable changes in elasticity across individuals. Although our results must be considered preliminary, findings of consistent responses across subjects may make it possible to derive standardized target values for Teflon augmentation surgery. The availability of such values might improve the outcomes of phonosurgery.

In the present study, we found that Young's modulus increased in a linear fashion with vocal fold displacement, at all levels of stimulation. Across stimulation levels, the elastic modulus values for the vocal fold at rest differed significantly from those measured under transcutaneous stimulation, but the 2 different stimulation levels did not differ significantly from one another. There are several possible explanations for this finding. First, fatigue effects may be present. The stimulation levels were not randomized in this study; instead, all subjects received the different conditions in the same order (rest, high stimulation, and low stimulation). This strategy ensured that differences among subjects were not confounded with presentation order, adding credibility to our finding that subjects did not differ in modulus values at any stimulation level. However, Table 1 shows that modulus values were much more variable in the low stimulation condition (which occurred last) than under high stimulation. This suggests that subjects differed in the extent to which fatigue affected them. Had measurements in the low stimulation condition varied less, differences between the 2 stimulation conditions might have reached statistical significance.

It is also possible that stimulation levels did not differ sufficiently to produce reliable differences in the Young's modulus values. The stimulation levels were chosen by observing the effect of stimulation on the vocal folds: stimulation at 3.8 mA consistently produced adduction to midline with prominent vocalis bulging, while stimulation at 3.2 mA resulted in visible relaxation of the folds. However, the current actually delivered to the nerve via transcutaneous stimulation may have differed from that generated by the stimulator; further, ceiling effects may have been present, with 1 or both stimulation levels producing contractions near the fold's physiologic limit. Our ability to separate these factors is limited in the in vivo model. However, further studies controlling for presentation order effects are clearly indicated.

This study represents the first attempt to measure Young's modulus in vivo. In the present study, the in vivo transverse elastic properties of body and cover tissues were reported as 1 entity. Because tissue exists in 3 dimensions, it potentially has different longitudinal, vertical, and transverse elastic moduli.[2,4,24,25] Previous studies have generally measured the elastic modulus in the longitudinal plane (anterior-posterior direction), which is the most isotropic. However, this modulus cannot be measured in the in vivo state because of the anterior and posterior attachments of the vocal folds. The transverse modulus can be measured in vivo without harm to the subject. Further, the differential transverse modulus is a dynamic measurement, and reflects the change in the vocal fold elasticity at any given tissue displacement. Finally, most of the vocal fold tissue wave movement is in the transverse direction (although the traveling wave motion in the vocal fold is in the vertical dimension). These factors combine to make the transverse modulus a logical choice for measurement in vivo.

Moduli reported in this study were much smaller than the values of the longitudinal modulus reported previously by Kakita et al.[2] Our values also differ from those of Alipour-Haghighi and Titze,[17] who

TABLE 2. ESTIMATION OF WAVE VELOCITY VALUES USING CALCULATED DIFFERENTIAL YOUNG'S MODULUS

	Rest	*High Stimulation*	*Low Stimulation*
Mean	338.1	446.8	418.3
SD	112.0	129.0	130.6
Minimum	156.5	242.5	204.1
Maximum	542.2	664.1	645.4

Data are centimeters per second.

reported longitudinal Young's moduli for the body and cover of 20.7 kilopascals and 41.9 kilopascals, respectively, at low strain (0% to 15%). These values are at least 4 to 5 times higher than our measurements, regardless of the stimulation current on the affected vocal fold. These differences were probably due to the sensitivity of our device, the choice of Young's elastic modulus, and the in vivo technique of measurement. That the transverse moduli also increased linearly with displacement suggests a low strain range (strain < 15%) of vocal fold tissue deformation. This may be significant in that the vocal folds operate mostly at low strains during phonation.[18]

This study measured Young's modulus in subjects under general anesthesia. Many phonosurgical techniques are currently performed under local anesthesia in awake patients. This device is not practically suited to such operations. A noninvasive technique to estimate the stiffness of the vocal folds should certainly be the subject of future investigation. The data from the present study provide valuable norms to which results of future studies may be compared. Toward this end, it is important to emphasize that measurement of Young's modulus values should permit the calculation of traveling wave velocity by the formula Traveling wave velocity = (Young's modulus/tissue density)$^{1/2}$.

The traveling wave velocities calculated from our measurements are given in Table 2. The traveling wave velocity has been observed to change in some laryngeal disorders that affect vocal fold stiffness, such as unilateral recurrent laryngeal nerve paralysis.[26] A method of measuring wave velocity in vivo has obvious implications for the diagnosis and treatment of such disorders.

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REFERENCES

1. Vennard JK. Elementary fluid mechanics. 2nd ed. New York, NY: John Wiley & Sons, 1947.

2. Kakita Y, Hirano M, Ohmaru K. Physical properties of the vocal fold tissues: measurement on excised larynges. In: Stevens KN, Hirano M, eds. Vocal fold physiology. Tokyo, Japan: University of Tokyo Press, 1981:377-97.

3. Baer T. Investigation of phonatory mechanism. In: Ludlow CL, O'Connell M, eds. Proceedings of the Conference on the Assessment of Vocal Pathology. Rockville, Md: ASHA Report, 1979;11:38-47.

4. Titze IR. Biomechanics and distributed mass models of vocal fold vibration. In: Stevens KN, Hirano M, eds. Vocal fold physiology. Tokyo, Japan: University of Tokyo Press, 1981:245-70.

5. Titze IR. The physics of small amplitude oscillations of the vocal folds. J Acoust Soc Am 1988;80:1532-6.

6. Titze IR. On the relation between subglottal pressure and fundamental frequency in phonation. J Acoust Soc Am 1989; 85:901-6.

7. Anathapadmanabha TV, Fant GI. Speech production: calculation of the true glottal flow and its components. Speech Transmission Laboratory — Quarterly Progress and Status Report, Sweden, 1, 1982.

8. Flanagan JL. Some properties of the glottal sound source. J Speech Hear Res 1958;1:99-116.

9. Trapp TK, Berke GS, Bell TS, Hanson DG, Ward PH. The effect of vocal fold augmentation on laryngeal vibration in simulated recurrent laryngeal nerve paralysis: a study of Teflon and Phonogel. Ann Otol Rhinol Laryngol 1989;98:220-7.

10. Hirano M. Structure and vibratory behavior of the vocal fold. In: Sawashima M, Cooper FS, eds. Dynamic aspects of speech production. Tokyo, Japan: University of Tokyo, 1977:13-30.

11. Hirano M. Phonosurgery: basic and clinical investigation. Otol Fukuoka (Jibi To Rinsho) 1975;21:239-440.

12. Saito S, Fukuda H, Kitahara S, et al. Pellet tracking in the vocal fold while phonating — experimental study using canine larynges with muscle activity. In: Titze IR, Scherer RC, eds. Vocal fold physiology: biomechanics, acoustics and phonatory control. Denver, Colo: Denver Center for the Performing Arts, 1985:169-82.

13. Titze IR, Talkin DT. A theoretical study of the effects of various laryngeal configurations on the acoustics of phonation. J Acoust Soc Am 1979;66:60-74.

14. Ishizaka K, Kaneko T. On equivalent mechanical constants of the vocal cords. J Acoust Soc Jpn 1968;24:312-3.

15. Perlman AL, Titze IR, Cooper DS. Elasticity of canine vocal fold tissue. J Speech Hear Res 1984;27:212-9.

16. Perlman AL, Titze IR. Measurement of viscoelastic properties in live tissue. In: Titze IR, Scherer RC, eds. Vocal fold physiology: biomechanics, acoustics and phonatory control. Denver, Colo: Denver Center for the Performing Arts, 1985:273-81.

17. Alipour-Haghighi F, Titze IR. Elastic models of vocal fold tissues. J Acoust Soc Am 1991;90:1326-31.

18. Hollien H. Vocal pitch variation related to changes in vocal fold length. J Speech Hear Res 1960;3:150-6.

19. Fukuda H, Muta H, Kahou S, et al. Response of vocal folds to externally induced vibration: basic study and its clinical application. In: Baer T, Sasaki C, Harris K, eds. Laryngeal

in phonation and respiration. San Diego, Calif: College-Hill Press, 1987:366-77.

20. LeJeune FE Jr. Vocal ligametry. Update. Ann Otol Rhinol Laryngol 1987;96:597-600.

21. Berke GS, Trapp TK, Gerratt BR, Hanson DG. An accurate method of Teflon injection using functional phonosurgery. Arch Otolaryngol Head Neck Surg 1988;114:1321-3.

22. Hirano M, Matsuo K, Kakita Y, Kawasaki H, Kurita S. Vibratory behavior versus the structure of the vocal fold. In: Titze IR, Scherer RC, eds. Vocal fold physiology: biomechanics, acoustics and phonatory control. Denver, Colo: Denver Center for the Performing Arts, 1985:26-40.

23. Sanders I, Aviv J, Biller H. Transcutaneous electrical stimulation of the recurrent laryngeal nerve. Otolaryngol Head Neck Surg 1986;95:152-7.

24. Achenbach JD. Wave propagation in elastic solids. Amsterdam, the Netherlands: Elsevier Science Publications, 1987.

25. Bland DR. Wave theory and applications. Oxford, England: Oxford University Press, 1988.

26. Sloan S, Berke G, Gerratt D. The effect of asymmetric laryngeal stiffness on traveling wave velocity in the canine larynx. Otolaryngol Head Neck Surg 1992;107:516-26.