# A Methodological Study of Hemilaryngeal Phonation

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# A Methodological Study of Hemilaryngeal Phonation

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**An excised hemilarynx setup was developed. The phonatory characteristics of nine excised canine larynges were examined. The left vocal fold of each larynx was then removed and substituted with a vertical plexiglass plate. The larynges were phonated again. Recordings were made of phonation threshold pressure, sound pressure level, average glottal flow, fundamental frequency, and amplitude of vocal fold vibration as observed with a video stroboscope. Measurements were made over a range of subglottal pressures. For the hemilarynx, simultaneous recordings of intraglottal pressure and vocal fold contact area were also made. It was found that amplitude and frequency of vocal fold vibration of the hemilarynx, as well as rates of change of amplitude and frequency as a function of subglottal pressure, were similar to those of the full larynx. Also similar were phonation threshold pressures and ranges of subglottal pressure over which the larynges phonated. The average airflow of the hemilarynx was approximately half that of the full larynx, and the sound pressure level, under similar conditions, was one fourth (about 6 dB less) in the hemilarynx.**

## INTRODUCTION

Vertical hemilaryngectomy has been practiced widely for more than 40 years, ever since Alonso[1] developed the procedure to a practical level. Some patients are able to produce relatively normal phonation after one vocal fold has been removed. However, there are few kinematic or aerodynamic data available to assess the vibration of a single vocal fold against alternate structures. As is well known, a person with a single eye or a single ear can function relatively well, with some limitations. Although much research has been conducted on laryngeal phonation in general, little attention has been paid to single vocal fold phonation.

With recent developments in basic research and clinical measurements of vocal function, parameters such as vocal fold contact area and contact stress are of great interest because of their direct physiologic and clinical relevance.[2] The hemilarynx technique allows vocal fold contact area profiles and contact stress to be measured directly during phonation. Experimentally, the procedure involves removing one vocal fold and replacing it with a glass or plexiglass prism containing either an electronic conductive surface or pressure transducers. However, before using the hemilarynx as a research tool to study phonation, the similarities and differences between the hemilarynx and full larynx need to be established. A better understanding of the physiology of single vocal fold phonation may then help clinicians improve surgical procedures, evaluate surgical results, and thereby achieve better phonation than is currently obtained. Additionally, from a research point of view, it is advantageous to observe the self-oscillating characteristics of a single fold because the second fold tends to obscure the lateral view and prevent observation of the vertical movements of the tissue.

The objective of this study was to develop a methodology for comparison of hemilaryngeal phonation with full-larynx phonation. The hypothesis is advanced that, except for a 2:1 scale factor for airflow, the hemilarynx behaves similarly to the full larynx. Phonation threshold pressures, transglottal pressure and flow ranges, fundamental frequency, and amplitude of vibration are all hypothesized to be the same.

## BACKGROUND ON EXCISED FULL LARYNX AND HEMILARYNX EXPERIMENTATION

Research into laryngeal physiology with excised larynges has been systematically reviewed by Cooper.[3,4] According to this author, the first known experiments on voice production using an excised larynx preparation were conducted by Leonardo da Vinci (1452–1519). By introducing air into the lung and narrowing or widening the "fistula" at the exit of the windpipe, Leonardo obtained phonation. In 1741, over 200 years after Leonardo's work, the French physician

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and anatomist Antoine Ferrein (1693–1769) presented his studies on phonation of excised larynges.[5,6] Ferrein carried out extensive experimentation on excised human larynges, as well as those of dogs, bulls, pigs, and sheep. He used his own lungs as the air source. He found that vocal intensity was controlled by glottal width and air velocity. Fundamental frequency was found to be primarily controlled by vocal fold tension and, possibly, also by contraction of the vocal folds.

There were new studies on phonatory physiology during the 19th century, including judgments of phonatory intensity and frequency, by Liskovius[7,8] and Lehfeldt.[9] Most notably, however, Johannes Müller[10,11] observed the relationship between vocal fold tension, subglottal pressure, and fundamental frequency. The apparatus used by Müller was very similar to the modern apparatus of van den Berg and Tan,[12] except that Müller used his own lung as the air source. Müller's apparatus simulated the contraction of all intrinsic laryngeal muscles isotonically or isometrically, except for the vocalis muscle.

In this century, van den Berg and colleagues[13–14] independently controlled airflow rate and configuration of the laryngeal cartilages in order to examine their effect on phonation, using excised human larynges. Van den Berg found that excised larynges could produce all the vocal registers. Longitudinal tension of the vocal folds was primarily responsible for determining vocal register and for controlling fundamental frequency within registers. Vertical phase differences in vibrations of the vocal fold were noted.

A similar experiment was also reported by Anthony.[15] In chest voice, fundamental frequency varied with subglottal pressure at a rate of 71.4 Hz/kPa, leaving vocal fold elongation constant. Excised larynx experiments were also reported by Hiroto,[16] who observed a wave-like motion of the vocal fold mucosa and proposed the mucoviscoelastic-aerodynamic theory of phonation.

Using an excised canine larynx, Baer[17] reported quantitative measurements of detailed mechanical vibration patterns. Small particles were attached to the vocal folds to serve as landmarks. The phonating excised larynges were observed stroboscopically to produce apparently stopped (or slow-motion) states, from both supraglottal and subglottal aspects. Measurements were made of the trajectories of the particles. Regulation of phonation was also observed. Baer found that points along the superior lip of the fold vibrate vertically while points in the lower margins move mostly horizontally.

More recently, Durham, *et al.*[8] reported on a hemilarynx procedure. Sustained phonation was achieved in their experiment and the movement of the vocal fold was observed from both the top and the side. The study was methodological only; therefore, no quantitative results were reported for sound quality, aerodynamics, and acoustics. Scherer, *et al.*[19] used an excised canine hemilarynx technique to measure vocal fold contact area and to compare it with the electroglottographic signal. In the Scherer, *et al.* set-up, the vocal fold was not self-oscillating, but driven by an electronic positioning arm.[19]

## METHOD

### *Larynges*

Nine larynges were harvested 15 minutes post mortem from large (25 to 30 kg) mongrel dogs. Every larynx was used twice, once for full-larynx vibration and then again for hemilarynx vibration. The larynges came from experimental animals from several coronary research units at The University of Iowa. None of the animals had been intubated with endotracheal tubes. Most of them had been used for experimental procedures involving surgical impairment of coronary circulation for a duration of less than 3 hours. The coronary units were not always able to supply dependable age or sex information for the animals; therefore, larynges from either sex were used and age was not recorded. Sex does not appear to affect the range and quality of phonation for canines.[18]

The length of the vocal folds in all the larynges was greater than 16 mm. Larger larynges were chosen for the following reasons: *1.* A large larynx usually has a thicker vocal fold, which phonates better because of a lower phonation threshold pressure.[19] *2.* It was easier to attach transducers and to make configurational adjustments on larger larynges.

### *Preparation of the Hemilarynx*

The following dissection procedure was used to avoid tissue damage. From a laryngofissure approach, the skin was cut and surrounding muscles were stretched. The trachea was identified from its easily recognizable ring structure, and dissected out. The trachea was cut 4 to 5 cm below the cricoid cartilage. The cutting end of the trachea was held by a 3-teeth traction forceps and retracted anteriorly and upward. The thyrohyoid and the sternothyroid muscle were cut. Another cut was made between the thyrohyoid membrane to disconnect the attached tissue, and the whole larynx was pulled out. Finally, the thyrohyoid ligaments (only 1 to 2 mm long in canines) and the rest of attached mucosa was cut so that the larynx was totally free from the body. The false folds were usually left attached to the free larynx until phonation, because they prevent the true vocal fold from drying out or being damaged during mounting of the excised larynx.

At least 4 cm of the trachea was left attached to the larynx for later ease of mounting. The larynx and the surrounding extrinsic muscles remained attached from the inferior edge of the hyoid bone to the cricoid cartilage.

After excision, the larynx was placed in a 0.67% saline solution[12] and stored in a refrigerator set at 40°F. The larynx was typically used in an experiment 12 to 36 hours after excision.

As described by Durham, *et al.*,[18] the remaining muscles were trimmed away from the thyroid cartilage and prepared for mounting. The cuneiform cartilages were removed. The epiglottis was removed at the level of the thyroid

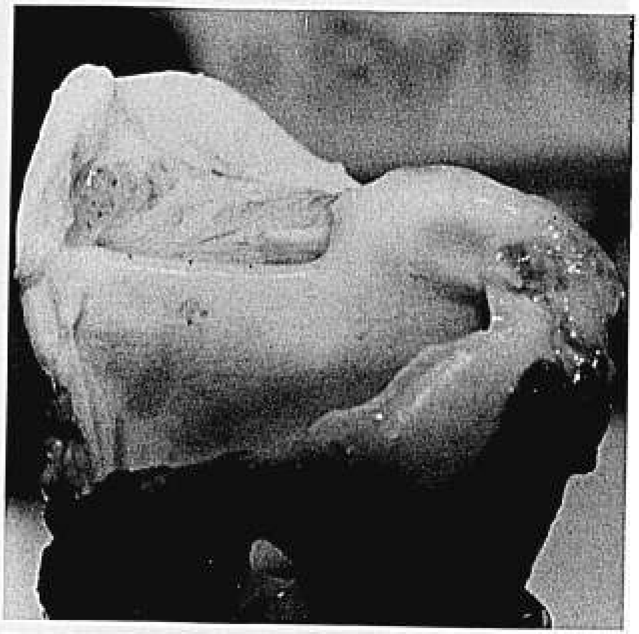

Fig. 1. Lateral view of a hemilarynx (anterior to the left, posterior to the right). Half of the thyroid cartilage and the left vocal fold are removed to facilitate mounting of the vertical plate.

notch by cutting through the aryepiglottic folds. Large surgical scissors were used to cut horizontally around and through the thyroid cartilage about 5 mm above the level of the true vocal folds. The cut removes the false vocal folds and exposes the true vocal folds.

In preparing a hemilarynx immediately after a full-larynx experiment, the left vocal fold, left arytenoid cartilage, and left half of the thyroid cartilage were removed (Fig. 1) to facilitate mounting of the vertical plate. A piece of 9-mm-thick plexiglass was carefully ground to a shape that exactly fit the left side of the subglottal space and the space vacated by the removed vocal fold, so that the remaining vocal fold achieved closure with the side of the vertical plate when the arytenoid cartilage was pushed (Fig. 2). The gap between the cricoid ring and the curved side of the plate was sealed by tightly clamping a curved steel strip (1-mm thick) with a stainless steel screw driven through a hole on both the cricoid cartilage and the plexiglass plate. Occasionally, a clay-like gum was also used to prevent air from escaping.

The arytenoid cartilage was positioned for phonation with a 3-pronged device (Fig. 2, middle-right of photograph). The 3-pronged device was attached to micrometers so that the vocal fold could be adducted by tightening the micrometer. A wood shim of a selected size was positioned between the arytenoid cartilage and the plexiglass plate (or between the two cartilages for full-larynx operation) to change the glottal configuration.

Another micrometer system was attached via a rod (upper-right of Fig. 2) to the anterior tip of the thyroid lamina (by stitching). Elongation of the vocal fold was controlled by turning this micrometer. The length of the vocal fold was first set to the in situ length by the micrometer adjustment. This in situ length served as the reference length. Recorded micrometer values were used for subsequent positive or negative changes in vocal fold length.

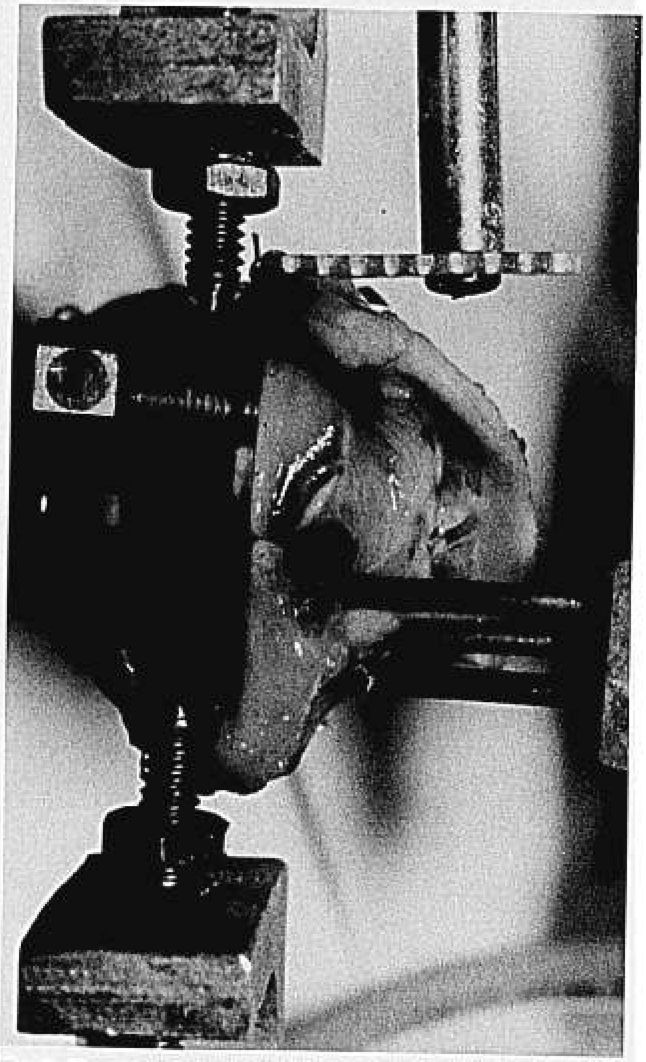

Fig. 2. Top view of the hemilarynx with plexiglass plate replacing the left vocal fold. The right fold is abutted against the plate, which is mounted by two screws (top and bottom). Additional mounting screws are seen shining through the plate from below. A three-pronged device (middle-right) is used to adjust the arytenoid cartilage, and a rod (upper-right) is used to adjust the vocal fold length.

To facilitate observation of vocal fold movement, a black 8-0 ophthalmic nylon suture with needle was used to stitch marks on the upper lip of the membranous portion of the remaining vocal fold (three tiny marks are barely visible on the vocal fold edge in Figure 2). The needle was pushed though the superficial layer of the vocal fold at a depth of about 0.5 mm, so that the stitch could be tightly attached to the vocal fold cover. This allowed visualization of a surface point without significant distortion and interference with vocal fold vibration.

## *The Apparatus, Larynx Mounting, and Control*

The entire apparatus used for experimentation on a full larynx was described in detail by Baer[17] and Durham, *et al.*[18] Figure 3 illustrates the excised larynx apparatus. An Ingersoll-Rand (Type 30) conventional air compressor was used to generate the airflow. Pressure was reduced to 15 psi using a Packer-Hannifin 49-21641 compressed air regulator.

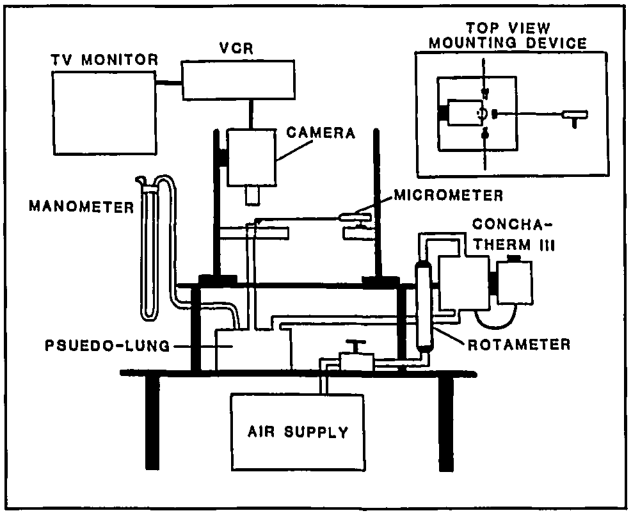


Fig. 3. Illustration of the excised larynx apparatus.

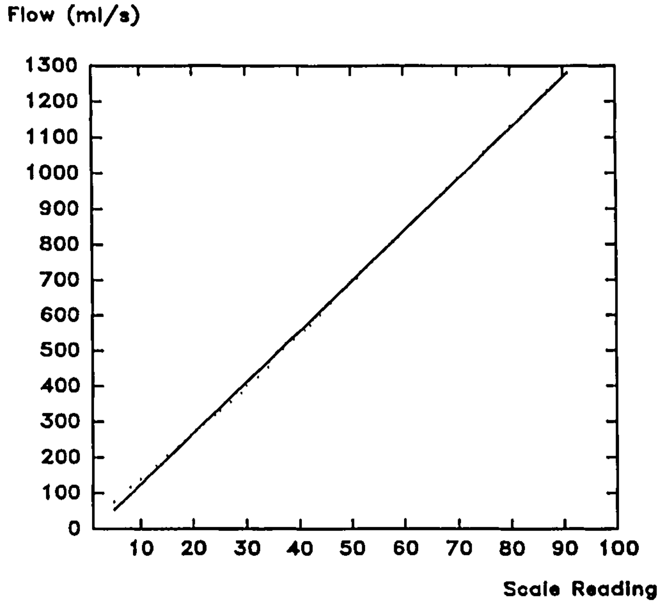


Fig. 4. Calibration chart for Gilmont J197 flowmeter. The flowmeter is linear in the range of 30 mL/s to 1200 mL/s.

The amount of airflow used during the experiment was controlled by a valve. The flow was measured as it passed through a Gilmont rotameter-type flowmeter (J197). The input air was conditioned to 35 to 38°C and 95% to 100% relative humidity by two ConchaTherm III heater-humidifiers (Respiratory Care, Inc.) placed in series. It took about 15 minutes for the heater-humidifiers to heat and humidify the air to these ranges. A Cole-Parmer Digi-Sense Thermocouple Thermometer (Model 8529-00) and a humidity probe (Check-It Electronics 424) were used to monitor the humidity 2 cm above the level of the vocal folds.

A plastic container with a volume of approximately 5000 mL was used as a damped acoustic resonator (a pseudolung) and a condensed water reservoir. This container was lined with soft urethane foam. It simulated the approximate open-end termination for acoustic waves propagating in a section of ¾-inch copper plumbing pipe mounted vertically on this container. The larynx was connected with a section of trachea on the top of the pipe. The length of the pipe was 15 cm.

Subglottic pressure, vocal fold elongation, and prephonatory configuration were varied independently as control variables. Glottal flow, fundamental frequency, sound pressure level, and vibrational amplitude were recorded and analyzed for both full larynx and hemilarynx. The assumption of the functional similarity between the full larynx and the hemilarynx was tested with these variables.

### *Instrumentation, Calibration, and Data Recording*

An RCA color video camera (Model TC 5001) was used to record the glottal image from above. The image was viewed on a Panasonic 12-inch black-and-white monitor. The camera was mounted 15 to 20 cm from the larynx with the view angle normal to the glottis. The vocal folds were magnified 15 to 20 times when viewed on the monitor. In addition to the top view video recording, a second video camera (Sony DXC-102) with a 90-mm microlens was mounted at the left side of the larynx, perpendicular to the vertical plexiglass plate, so that the contact area image could be recorded and viewed on another Panasonic 12-inch black-and-white monitor.

A special video-effect generator (Panasonic VY-922) was used to project both superior and lateral images on the same screen. The split image was refolded on a Panasonic PV1560 VHS VCR. On playback, the split image was viewed on a color Sony Trinitron 25-inch monitor. The edge-to-edge distortion of the TV screen measured less than 5%. The duration of each frame was about 33.3 msec. The speed of the video camera was 1/1000 second per frame. Before fixing the camera adjustments in each experiment, a piece of scale paper was placed on the vocal fold for magnification calibration.

A strobe light (Pioneer DS330-ST) was placed 10 cm from the glottis, at an angle of 45 degrees from the vertical. The frequency of the strobe light could be adjusted manually to any value below 1000 Hz, or it could be triggered automatically by an outside electronic device. In order to obtain still-video images, an electronic timing delay device was designed and built for triggering the strobe light. The trigger signal was a low-passed version (Wavetek-Rockland 432, 300-Hz cutoff) of the acoustic signal. The stroboscope could thus be triggered at controlled adjustable timing delays. Stable images could be locked in at any phase of the phonation cycle. The flash firing, detected by a photo diode, was recorded simultaneously on the audio channel of the VCR so that corresponding phase information about the locked still-video image could be obtained.

The acoustic signal was recorded using a Sennheiser MD441-U microphone, positioned 15 cm from the glottis. The axis of the microphone was at 45 degrees from the long axis of the larynx in order to avoid airflow impinging directly onto the microphone. The signal picked up by the microphone was preamplified, then recorded by the left audio channel of the VCR. It was also monitored and analyzed on one channel of a DATA 6000 universal signal analyzer. Alternately, the signal was A/D converted and processed on a VAX 3200 computer.

Mean subglottal pressure in the pseudolung was measured with an open-ended water manometer (Dwyer No.

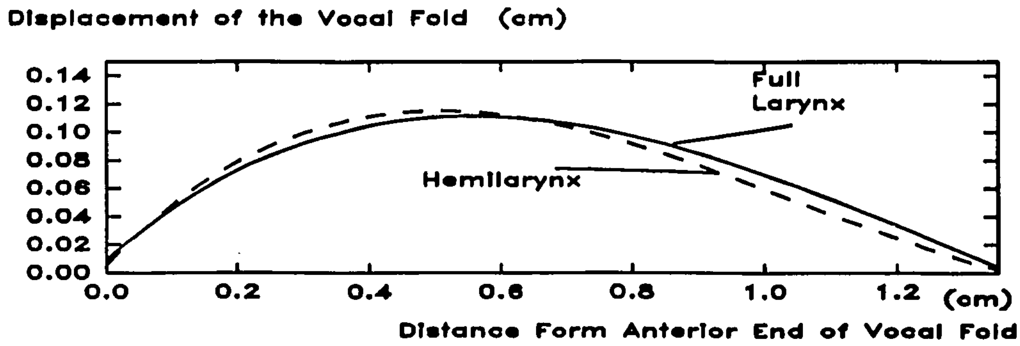


Fig. 5. Comparison of vocal fold displacement between hemilarynx and full larynx as viewed from the top.

1211). The pressure was read out orally and recorded on the right audio channel of the VCR, which was being used as a chatter channel.

The microphone head of the sound level meter (Quest 215) was positioned 15 cm from the glottis and angled at 45 degrees. The C scale was used, which filters out frequency components below 50 Hz. This low-pass filtering decreases the artifact caused by low-frequency air currents in the recording room. The sound pressure level was read out orally and recorded on the chatter channel of the VCR.

The average glottal flow, which was equal to the applied airflow from the compressor, was measured with a flowmeter (Gilmont J197). The measurement was made by taking the midball reading from the flowmeter and looking up the flow on its calibration chart (Fig. 4). The flowmeter was linear in the range from 30 mL/s to 1200 mL/s. The measurement read-outs were recorded on the chatter channel of the VCR.

### *Data Analysis*

After laryngeal manipulations were completed, subglottal pressures, glottal flows, and the sound pressure levels were tabulated manually while listening to the chatter channel playback. The fundamental frequency of vocal fold vibration was determined from the acoustic signal with a Precision Data 6000 Universal Waveform Analyzer. Measurement of vocal fold movement was made by turning the jog dial of the VCR and reviewing the video tape frame-by-frame.

The amplitude of vocal fold vibration was measured on the video screen. As described, there was a phase difference between the top lip and the bottom lip. When the top lip and bottom lip were at the same distance from the midsagittal plane, the glottal area reached its maximum value. The amplitude of vocal fold vibration was defined as half of the maximum glottal width at this point. Although this is an underestimate of the maximum lateral tissue excursion, it was the most consistent measurement and served well for comparisons between the hemilarynx and the full larynx.

## GENERAL RESULTS

### *Gross Performance of the Hemilarynx*

Self-oscillation of the vocal folds occurred when the subglottal pressure exceeded a threshold value. The typical phonation threshold pressure was 0.78 kPa, but this varied highly with fundamental frequency, as noted by Finkelhor, *et al.*[20] After a brief break in phonation, oscillation was sustained and the subglottal pressure remained at a level of 0.2 to 0.4 kPa higher than threshold pressure (for a constant flow source). Perceptually, the sound of the hemilarynx and the full larynx were similar, except that the full larynx was louder. With increases of subglottal pressure, average glottal flows, sound pressure levels, fundamental frequencies, and amplitudes of vocal fold vibration all increased. There usually was range of subglottal pressures above threshold that produced "good phonation." In this range, phonation had the characteristics of chest voice, that is, phonation was generally stable, loud, and rich in timbre. Phonation within this range was defined as normal phonation. As subglottal pressure continuously increased and exceeded the normal range, a second range was reached, typically between 2 to 3 kPa. In this range, vibration became very irregular and the sound became rough. The maximum subglottal pressure producing stable phonation was defined as phonation instability pressure. The tendency toward instability was observed for both excised hemilarynges and excised full larynges.

Vocal fold movement was observed in apparent slow motion under stroboscopic illumination. From the top view, vocal fold vibration of the hemilarynx was similar to that of the full larynx: the bottom lip of the vocal fold touched first, then the top lip, then both lips moved vertically upward, and finally the top lip separated gradually. When the top separated, the bottom lip was shadowed by the top lip and was invisible from the superior view. Before the top lip reached its maximum excursion, the bottom lip became visible and began to move toward the midline. Equivalently, a mucosal wave traveled from the bottom lip to the top lip.

From the side view in the hemilarynx, the bottom lip made contact with the vertical plane first, then the top lip made contact, then both lips moved up in the sagittal plane. The bottom lip then separated, followed by top lip separation.

The half glottal shape of the hemilarynx looked similar to that of the full larynx during vibration. This glottal shape was measured on the video monitor when lateral displacement reached its maximum value. Figure 5 shows differences in displacement be-

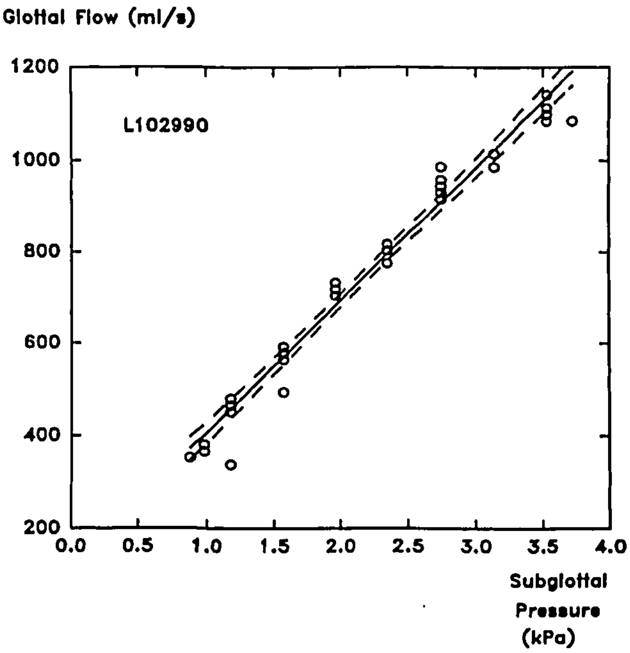


Fig. 6. Glottal flow *vs.* subglottal pressure with a 99% confidence range.

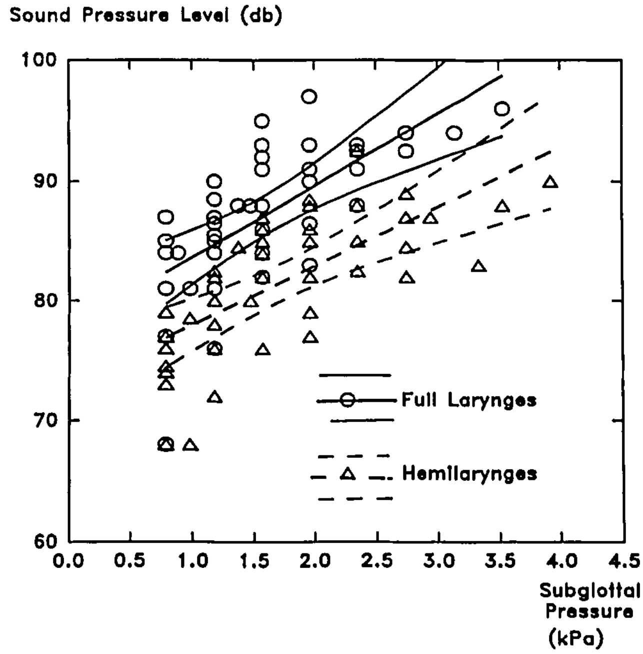


Fig. 7. The six repeated data groups for sound pressure level *vs.* subglottal pressure with 99% confidence range.

tween the hemilarynx and full larynx. The displacement function resembled a half sinusoid (coefficient of variation = 5.01%).

### *Repeatability of the Measurements*

Many factors are likely to affect measurements on excised larynges. These factors include reliability of the instrumentation, stability of the phonation setup, and stability of the tissue properties. Preliminary experiments were conducted to assess measurement repeatability prior to the full-larynx–hemilarynx comparative measurements. Each measurement was repeated six times on randomly chosen larynges. The time interval between each measurement was about 10 minutes. Thus, the total duration for one repeatability assessment on a given larynx was about 60 to 70 minutes.

Figure 6 displays repeated glottal flow measurements at different subglottal pressures for one typical larynx. The 99% confidence range was also calculated and plotted. The repeatability error was less than 5%. The data fit a first-order regression line ($r$ = .98) in this range, but a higher order function is suggested by the deviations at the endpoints.

Figure 7 displays repeated sound pressure level (SPL) measurements at the same subglottal pressures, with a 99% confidence range. Measurement error was less than 3 dB.

Figure 8 displays repeated fundamental frequency measurements at the different subglottal pressures, with a 99% confidence range. This graph shows the measurement error was less than 10 Hz. The data can be approximated by a first-order linear model ($r$ = .98) in this range, but a second-order model could also be used if theoretical consideration would warrant it. The average slope is 40 Hz/kPa, which relates closely to the results of Baer[17] and Titze.[22]

Figure 9 displays repeated measures of vocal fold vibrational amplitude at the different subglottal pressures, with a 99% confidence range. Only four measurements are plotted because the strobe light accidently did not trigger well in two larynges. The measurement error was less than 10%.

Although the within-larynx repeatability of the measurements was satisfactory, the variances of the measurements across larynges were large because there are great individual differences between larynges. Averages across-larynges measurements must be interpreted with caution, therefore.

## SPECIFIC COMPARISONS BETWEEN HEMILARYNGES AND FULL LARYNGES

The purpose of this analysis was to compare parameters of the hemilarynx with those of the full larynx. Statistics were used to estimate measurement accuracy. The averaged value of each measurement, along with an error range, was calculated and plotted. Curve fitting was used to obtain an average trend, which represented the relationship between dependent and independent variables.

### *Phonation Threshold Pressure and Range of Subglottal Pressure*

Phonation threshold pressure was defined by

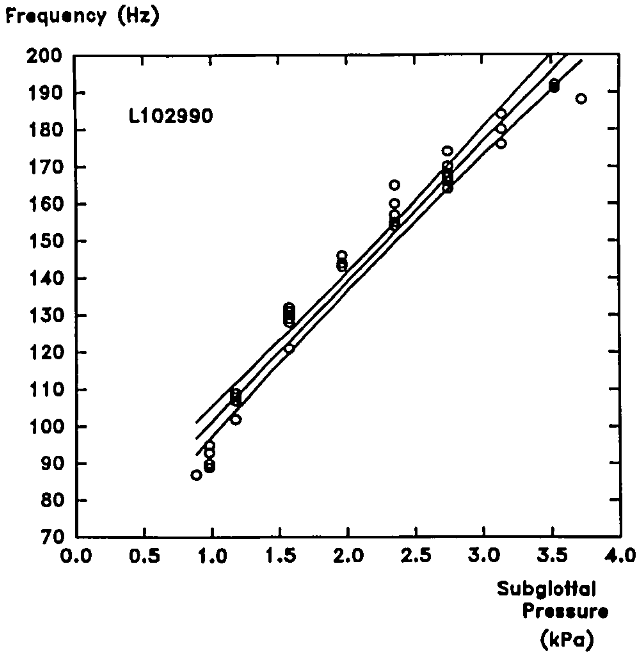


Fig. 8. The six repeated data groups for fundamental frequency of acoustic output *vs.* subglottal pressure with a 99% confidence range.

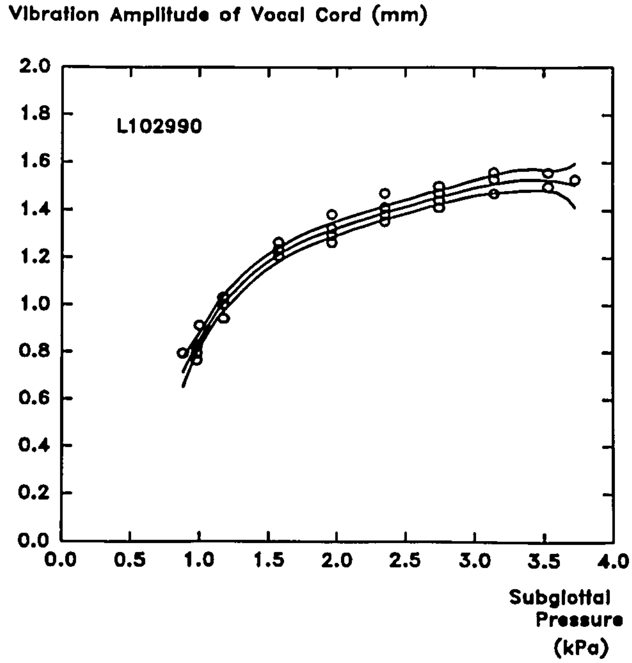


Fig. 9. The four repeated data groups for the amplitude of the vocal fold vibration *vs.* subglottal pressure with a 99% confidence range.

Titze[20] as the minimum pressure required to initiate small amplitude vocal fold vibration. It depends on the glottal configuration (adduction, convergence angle of the glottis, vocal fold thickness) and biomechanical properties of vocal fold tissues (elasticity and viscosity). On purely theoretical grounds, Titze predicted phonation threshold pressures of 0.2 to 1.0 kPa.

In the current experiments, there was no detectable statistical difference between nine full larynges and their respective hemilarynx counterparts, both in terms of a mean value or a standard deviation (Fig. 10). The range was similar to ranges found by Baer[17] and Finkelhor, *et al.*[21] for low elongation, but it was about 0.2 to 0.3 kPa greater than the threshold pressure reported by van den Berg[12] for an excised human larynx, and 0.3 to 0.5 kPa greater than Isshiki's[23] thresholds from a human subject. These results suggest that the human larynx (with living tissue) may have some advantage in ease of phonation over an excised canine larynx. Higher phonation threshold pressures in the excised larynx, which has no supraglottal vocal tract, may also suggest that the vocal tract plays a role in facilitating self-oscillation of the vocal folds.

It was found that a dehydrated vocal fold resulted in increased phonation threshold pressures.[21,24] A larynx with a damaged vocal fold also has higher phonation threshold pressures than a normal larynx.[25] In the same excised larynx study, there was the impression that increases in phonation threshold pressures affected the intensity range more than maximum intensity. This speculation may relate somehow to the strain/strangled voice, which is characterized by a hard-to-start phonation and a narrow intensity range, and especially by the loss of quiet phonation. The current experiment failed to show that, under hemilaryngeal conditions, ease of the phonation is impaired.

Another important variable is phonation instability pressure. This is the subglottal pressure for which phonation becomes aperiodic at the high end of the intensity range. For the nine pairs of hemilarynges and full larynges, in which elongation and shim placement were controlled, the average phonation instability pressures in the hemilarynges were about 20% greater than those of the full larynges (Fig. 11). Assuming that a systematic error did not play a role, it is possible that this difference in phonation instability pressure was due to differences between glottal flow velocity profiles. More studies are needed to investigate this difference in the future.

### *Average Glottal Flow*

Figure 12 shows average glottal flow versus subglottal pressure at a constant elongation and prephonatory configuration. The microphone was positioned at 15 cm, 45 degrees from the larynx. The overall average flow of the hemilarynx was about half that of the full larynx over the entire phonation range. The slope of the average glottal flow function was 0.3 L/kPa in the full larynx, about twice that of the hemilarynx. By way of comparison with earlier studies, this slope is the average of van den Berg's data (0.2 to 0.4 L/kPa). In the full larynx, average glottal flow

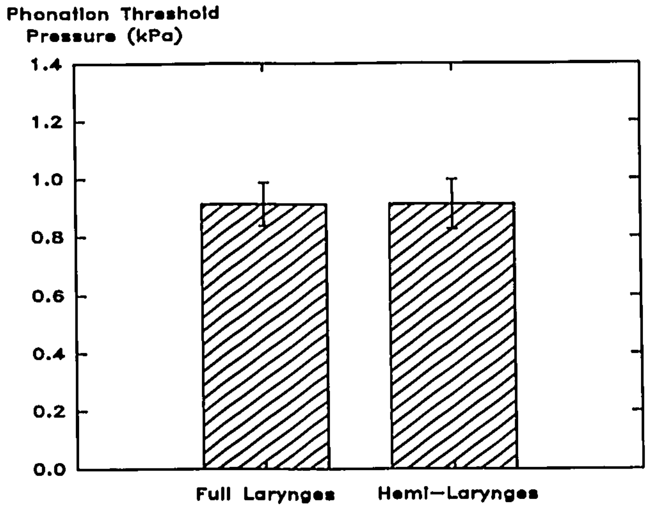


Fig. 10. Comparison of phonation threshold pressures between full larynges and their hemilarynx counterparts.

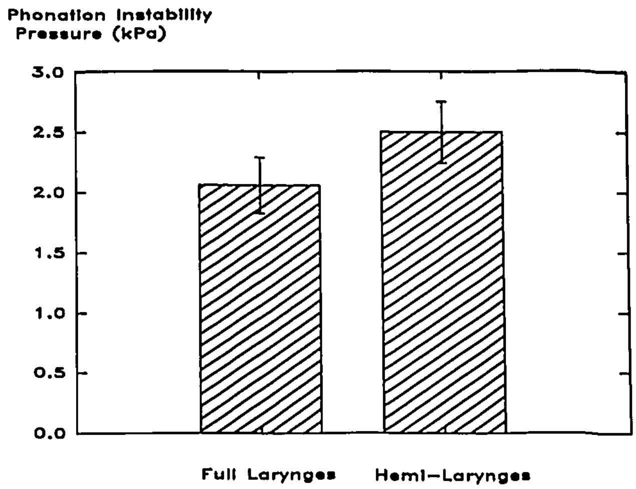


Fig. 11. Comparison of phonation instability pressure between full larynges and their hemilarynx counterparts.

had a positive linear relationship with subglottal pressure, and ranged from 0.2 to 1.2 L/s, while subglottal pressures ranged from 0.8 to 4.0 kPa.

The typical range of flow in human subjects is 0.1 to 0.3 L/s.[22] In Baer's[17] experimental study on excised canine larynges, flow rate ranged from 0.1 to greater than 0.5 L/s. The present data displayed great concentration in the 0.2 to 0.5 L/s range. Although flow rates were higher than those typical for human phonation, they were similar to those of Baer and other reported data with excised larynges[12] and live canines.[25]

### *Sound Pressure Output Regulation of the Hemilarynx*

Figure 13 shows sound pressure level versus subglottal pressure at constant elongation and prephonatory configuration. The microphone was positioned at 15 cm, 45 degrees from the larynx. The average sound pressure ranged from 80 to 96 dB in the full larynx and from 75 to 90 dB in the hemilarynx. The dynamic range of the sound-level output was about 15 dB.

Assuming that glottal flow is nearly proportional to glottal area,[27,28] and realizing that power is proportional to flow squared,[29] the power of the acoustic output of the hemilarynx is predicted to be one fourth that of the full larynx. In terms of sound pressure level, this corresponds to 6 dB, the difference observed.

According to informal clinical experience, the superior hemilaryngectomy patients seem to have phonation that is slightly softer than that of normal subjects, and perhaps a little more pressed. The present data may help explain this phenomenon. Since a hemilarynx produces 6 dB less power at the same subglottal pressure, patients may press harder to obtain comparable output. Alternately, if the same sound power is expected, the hemilarynx may need twice as much subglottal pressure to drive it, which may exceed the phonation instability pressure and cause unstable phonation.

### *Fundamental Frequency*

Figure 14 shows fundamental frequency versus subglottal pressure at a constant elongation and prephonatory configuration. Averaged over the nine larynges, fundamental frequency had a positive linear relationship with subglottal pressure, ranging from 60 to 250 Hz, while subglottal pressure ranged from 0.7 to 3.7 kPa. The overall average frequency of the hemilarynx was slightly lower (about 25 Hz) than that of the full larynx over the phonation range. The slope of fundamental frequency increase over subglottal pressure was 50 Hz/kPa in the hemilarynx and 56 Hz/kPa in the full larynx. There was no statistical difference between them.

For the excised human larynx, the typical frequency range obtained by van den Berg and Tan[12] was 60 to 220 Hz in the subglottal pressure range of 0.5 to 2.9 kPa. In Baer's[17] data, subglottal pressure ranged from 0.5 to 1.7 kPa, with the greatest concentration in the 0.7 to 0.9 kPa range, whereas fundamental frequency ($F_O$) ranged from 80 to 140 Hz, with the greatest concentration in the 80 to 110 Hz range. The frequency range that Titze[22] reported was 75 to 200 Hz. He measured and predicted the relation between subglottal pressure ($P_S$) and fundamental frequency in phonation based on dynamic tension.

$F_O$–$P_S$ slopes from the cited sources[13,17,21] all seem to cluster around 30 to 70 Hz/kPa. Our frequency data from both the hemilarynx and the full larynx were very similar, approximately 50 Hz/kPa. Titze predicted that the slope should decrease with vocal fold length, but that was not verified in this study.

Clinically, $F_O$ change does not seem to be a problem for partial vertical laryngectomy patients. Al-

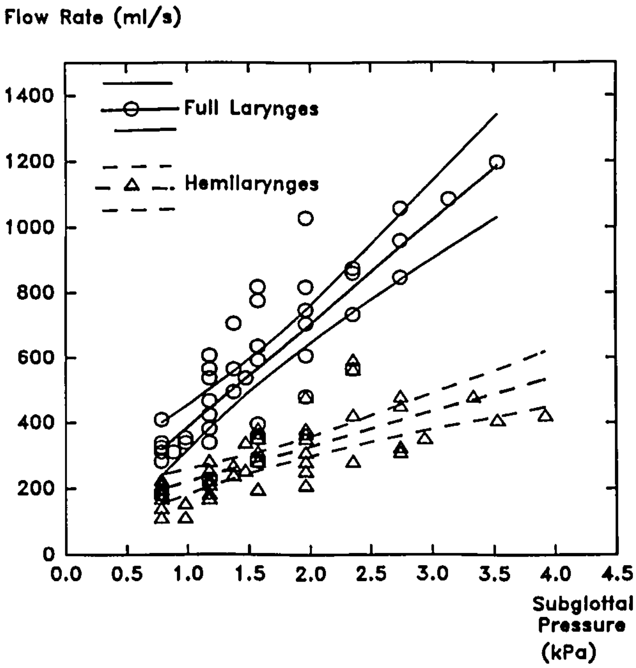


Fig. 12. Average glottal flow *vs.* subglottal pressure at the same elongation and prephonatory configuration for hemilarynges and full larynges (n = 9).

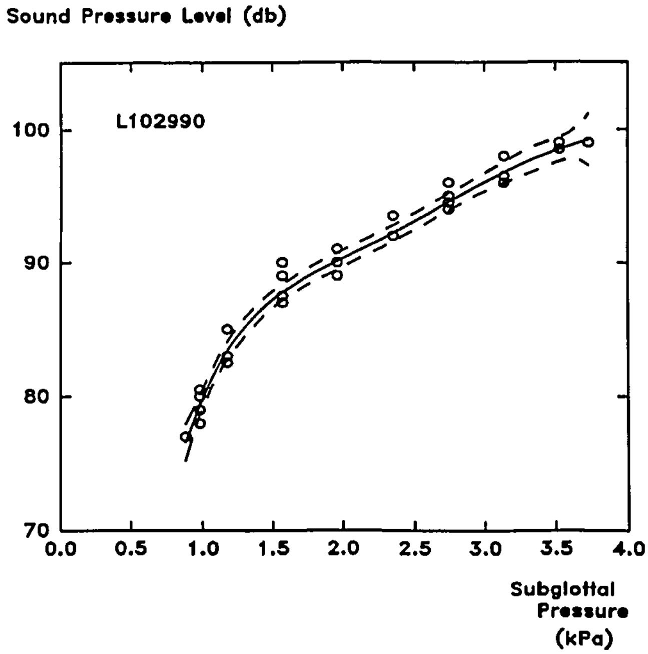


Fig. 13. Sound pressure level *vs.* subglottal pressure for hemilarynges and full larynges at the same elongation and prephonatory configuration (n = 9). The microphone was positioned 15 cm, 45 degrees from the larynx.

though there are no clinical data available on frequency regulation as a function of subglottal pressure for the hemilarynx, it would appear that no major abnormalities should occur, based on the present findings.

### *Vibrational Amplitude*

Figure 15 shows vibrational amplitude versus subglottal pressure at a constant elongation and prephonatory configuration. Amplitude of vibration increased with subglottal pressure, and ranged from 0.05 cm to 0.2 cm in both the full larynx and the hemilarynx. The average amplitude of vocal fold vibration was about 0.01 mm (about 10%) greater in the hemilarynx than in the full larynx in the lower subglottal pressure range, and identical in the high subglottal pressure range. However, this difference was within the 99% confidence range, and was not statistically significant.

The effect of air viscosity on flow in the hemilarynx should be considered as one source of discrepancy. According to basic fluid dynamics, when a fluid moves over a solid surface, the relative velocity between the solid surface and the contacting layer of fluid is zero. The velocity at the surface of the vocal folds should be zero, therefore. According to velocity profiles along the glottis calculated by Alipour and Patel,[30] the boundary layer of airflow is about one tenth of the total glottal width. In the hemilarynx, because the glottis is the space between the vocal fold and a still vertical plate at the midline, the velocity profile has an additional boundary layer, and is not a mirror image of the profile of the full larynx. Even if the vocal fold were to vibrate at the same amplitude and the glottal width were to be exactly half of that of the full larynx, the flows could not be identical in the half-glottis region. Due to nonlinear pressure-flow relations that depend on absolute values of glottal widths, glottal resistance would not scale in a simple 2:1 ratio. If pressures and flows are similar, therefore, some differences in amplitude of vibration can be expected.

In former experiments with excised canine larynges, a typical range of amplitude of vibration was reported to be 0.5 to 1.8 mm when elongation was zero.[21] This result is similar to the 0.5- to 2.0-mm range. The trend of the current data grossly fits the trend in Titze's data, as well as his mathematical predictions that amplitude varies with the square root of subglottal pressure.[22] The slope of the amplitude increase with subglottal pressure appeared to be slightly less for the hemilarynx than for the full larynx. This may again be caused by the nonlinear flow properties, but the exact differences are still topics which need more study.

## SUGGESTIONS FOR PHONOSURGERY

A practical question is: What is the desirable procedure for reconstruction when one remaining vocal fold is normal? It is obvious that if the impaired vocal fold can be reconstructed such that normal geometric and biomechanical properties are regained, normal phonation will result. Another clear-cut situa-

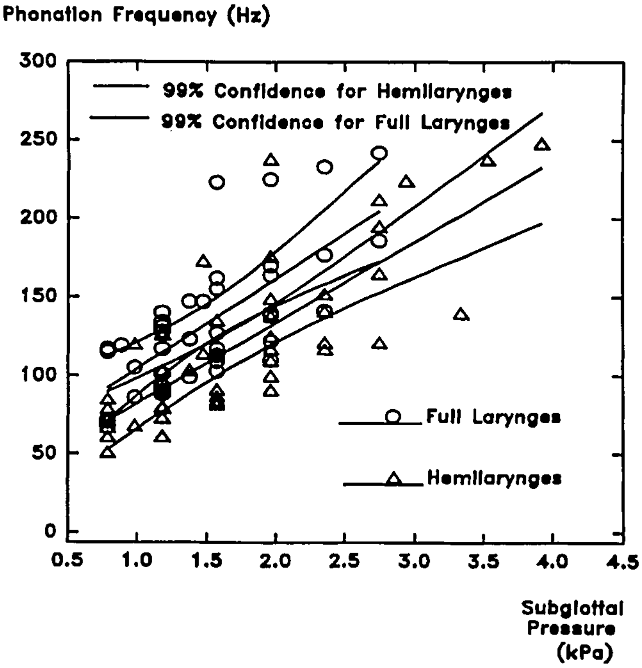


Fig. 14. Fundamental frequency *vs.* subglottal pressure for hemilarynges and full larynges at the same elongation and prephonatory configuration (n = 9).

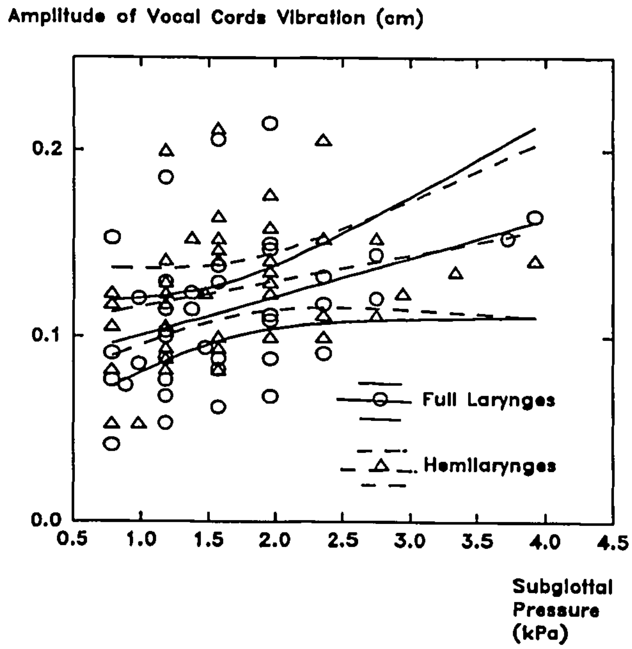


Fig. 15. Vocal fold vibration amplitude *vs.* subglottal pressure for hemilarynges and full larynges at the same elongation and prephonatory configuration (n = 9).

tion is the one where one side of the vocal fold is not repairable (such as in carcinoma of the larynx). In this situation, the current experiments suggest that it is still possible to produce near-normal phonation if the single vocal fold can vibrate against a rigid vertical wall and the necessary adjustments on prephonatory settings of the remaining vocal fold can be achieved.

Situations between these extreme cases are more difficult to deal with. In previous studies,[25,31] it was found that unilaterally scarred vocal folds, even though they still have a grossly normal shape, produce low intensity (on the average 12 dB less than normal) and unstable phonation with a high phonation threshold (about 1.2 kPa higher than normal). This might suggest that even if a vocal fold can be reconstructed grossly, but the biomechanical and geometrical characteristics of the fold cannot be restored, then the results of reconstruction might be worse than for a simple wall-like structure. According to computer simulations of vocal fold vibration[32] and clinical observations,[33] asymmetries between the vocal folds can cause aperiodic voice. There are two choices for surgeons to make for treating a damaged vocal fold: *1.* repair it to make it normal enough to cooperate with the opposite normal vocal fold and produce symmetric phonation, or *2.* simply modify it as a wall-like structure which is stiff enough not to interfere with the vibration of the opposite vocal fold, and thereby sacrifice 6 dB intensity.

A fully controllable arytenoid cartilage is also important in reconstructive surgery. In this study, satisfactory phonation occurred only in certain combinations of arytenoid adduction, elongation, and tension of the top and bottom lip. A well-reconstructed larynx should have three-dimensional movement control of the arytenoid cartilage, which is not only important for voice production, but also for respiration.

## CONCLUSION

Based on the data of these experiments, the hemilarynx is similar to the full larynx in terms of phonation threshold pressure, phonation instability pressure, fundamental frequency, and vibrational amplitude. Differences were all less than 10%. Average airflow was scaled 2:1 and acoustic power was scaled 4:1, or 6 dB less in the hemilarynx than in the full larynx. These results suggest that an excised hemilarynx is a reasonable substitute for an excised full larynx for experimental purposes in which access to the medial plane of the vocal fold is needed.

## BIBLIOGRAPHY


1. Alonso, J.M.: Conservative Surgery of Cancer of the Larynx. *Trans Am Acad Ophthal Otolaryngol*, 51:633, 1947.
2. Titze, I.R.: Parameterization of the Glottal Area, Glottal Flow, and Vocal Fold Contact Area. *J Acoust Soc Am*, 75:570–580, 1984.
3. Cooper, D.S.: Research in Laryngeal Physiology With Excised Larynges. In: *Otolaryngolgy—Head and Neck Surgery* (Vol. 3). C.W. Cummings (Ed.). C.V. Mosby, St. Louis, pp. 1766–1776, 1986.
4. Cooper, D.S.: Voice: A Historical Perspective. *J Voice*, 3:187–203, 1989.
5. Ferrein, A.: *De la formation de la voix de l'homme. Suite des mémoires de mathématique et de physique tirés des registres de l'Academie royale des sciences de l'année MDC–CXLI.*

Pierre Mortier, Amsterdam, pp. 545–579, 1746.
6. Ferrein, A.: *De la formation de la voix de l'homme. Histoire de l'Académie royale des sciences. Année MDCCXLI. Avec les Memoires de Mathématique et de Physique, pour la meme Année.* l'Imprimerie Royale, Paris, pp. 409–432, 1744.
7. Liskovius, C.: *Dissertatio physiologica sistens theoriam vocis/Theorie der Stimme.* Breitkoft und Haertel, Leipzig, 1814.
8. Liskovius, K.: *Physiologie der menschlichen Stimme.* Verlag von Joh., Amb. Barth., Leipzig, 1846.
9. Lehfeldt, C.: *Nonnulla de vocis formatione.* Typis Nietackianis, Berlin, 1835.
10. Müller, J.: *Handbuch der Physiologie des Menschen* (Vol. 2). Sect. I. Von der Stimme und Sprache. Verlag von J. Holscher, Coblenz, 1837.
11. Müller, J.: *Über die Compensation der physischen Kräfte am menschlichen Stimmorgan.* Unger, Berlin, 1839.
12. van den Berg, J.: Myoelastic-Aerodynamic Theory of Voice Production. *J Speech Hear Res*, 1:227–244, 1958.
13. van den Berg, J. and Tan, T.S. Results of Experiments With Human Larynges. *Practa OtoRhinoLaryngol, (Basel)*, 21:425–450, 1959.
14. van den Berg, J.: Vocal Ligaments Versus Registers. *Current Problems in Phoniatrics and Logopedics*, 1:19–34, 1960.
15. Anthony, J.K.F.: *Study of the Larynx II.* Works in Progress No. 2, 77–82, Department of Phonetics and Linguistics, University of Edinburgh, Scotland, 1968.
16. Hiroto, I.: The Mechanism of Phonation—Its Pathophysiological Aspects. *OtorhinoLaryngol Clinic (Kyoto)*, 39:229–291, 1966.
17. Baer, T.: *Investigation of Phonation Using Excised Larynges.* Massachusetts Institute of Technology, Boston, Mass., 1975. Doctoral Dissertation.
18. Durham, P.L., Scherer, R.C., Druker, D.G., *et al.*: *Development of Excised Larynx Procedures for Studying Mechanisms of Phonation.* Technical Report VABL-1-1987.
19. Scherer, R.C., Druker, D.G. and Titze, I.R.: Electroglottography and Direct Measurement of Vocal Fold Contact Area. In: *Vocal Fold Physiology: Voice Production, Mechanisms and Functions.* O. Fujimura (Ed.). Raven Press, New York, pp. 279–292, 1988.
20. Titze, I.R.: The Physics of Small-Amplitude Oscillation of the Vocal Folds. *J Acoust Soc Am*, 83:1536–1552, 1988.
21. Finkelhor, B.K., Titze, I.R. and Durham, P.L.: The Effect of Viscosity Changes in the Vocal Fold on the Range of Oscillation. *J Voice*, 1:320–325, 1988.
22. Titze, I.R.: On the Relation Between Subglottal Pressure and Fundamental Frequency in Phonation. *J Acoust Soc Am*, 85:901–906, 1989.
23. Ishikki, N.: Regulatory Mechanism of Voice Intensity Variation. *J Speech Hear Res*, 7:17–29, 1964.
24. Verdolini-Marston, K., Titze, I. and Druker, D.: Changes in Phonation Threshold Pressure With Induced Conditions of Hydration. *J Voice*, 42:142–151, 1990.
25. Wexler, D., Jiang, J., Gray, S., *et al.*: Phonosurgical Studies: Fat-Graft Reconstruction of Injured Canine Vocal Folds. *Ann Otol Rhinol Laryngol*, 98:668–673, 1989.
26. Koyama, T., Harvey, J.E. and Ogura, J.H.: Mechanism of Voice Production. II. Regulation of Pitch. LARYNGOSCOPE, 81:47–65, 1971.
27. Flanagan, J.L.: Some Properties of the Glottal Sound Source. *J Speech Hear Res*, 1:99–116, 1958.
28. Flanagan, J.L.: More-System Interaction in the Vocal Tract. *Ann NY Acad Sci*, 155:9–17, 1968.
29. Titze, I.R.: Regulation of Vocal Power and Efficiency by Subglottal Pressure and Glottal Width. In: *Vocal Fold Physiology: Voice Production, Mechanisms, and Functions.* O. Fujimura (Ed.). Raven Press, New York, pp. 227–238, 1988a.
30. Alipour, F. and Patel, V.C.: A Two-Dimensional Model of Laryngeal Flow. 121st Acoustical Society of America Meeting, 1991.
31. Jiang, J. and Titze, I. Measurement of Vocal Fold Intraglottal Pressure and Impact Stress. In Press.
32. Ishizaka, K. and Isshiki, N. Computer Simulation of Pathological Vocal Cord Vibration. *J Acoust Soc Am*, 60:1193–1198, 1976.
33. Hanson, D.G., Gerratt, B., Kanin, R., *et al.*: Glottographic Measures of Vocal Fold Vibrations: An Examination of Laryngeal Paralysis. LARYNGOSCOPE, 98:541–549, 1988.

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