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Direct Measurement of Subglottic Pressure and Laryngeal Resistance in Normal Subjects and in Spasmodic Dysphonia

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Summary: This study tested the accuracy of indirect methods of measurement of laryngeal airway resistance in normal subjects and in spasmodic dysphonia (SD). The indirect method assumes that subglottic air pressure remains constant during the voiced segment of a syllable. In this study subglottic air pressure was directly measured via puncture of the cricothyroid membrane in seven normal subjects and seven subjects with SD. The true laryngeal airway resistance was calculated and compared with airway resistance measured using indirect techniques based on intraoral air pressure. In five of the seven normal subjects, subglottic air pressure did not remain constant during the voiced segment. As a result, the error produced using indirect method of calculating average laryngeal resistance for the normal subjects varied from −44% to +50%. For SD subjects the error ranged from −49% to +22%. In general, the indirect technique overestimated laryngeal airway resistance in normal subjects and underestimated the resistance in subjects with SD. **Key Words:** Aerodynamic measurements—Subglottic air pressure—Laryngeal airway resistance.

INTRODUCTION

Adductor SD produces a strained voice with characteristic pitch breaks during vowel initiates. Previous studies have shown that resistance to air flow through the glottic is increased in SD (1–3). Laryngeal air resistance may therefore serve as a judge of disease severity is SD. However, the most widely used method used for measuring laryngeal air resistance is an indirect technique that is only an estimate of the true resistance. In particular, the indirect technique assumes that subglotttic air pressure remains constant during a voiced speech segment. This assumption may not be valid in individuals with SD. The goal of this study was to directly measure laryngeal air resistance in normal subjects and in individuals with SD throughout a voiced speech segment. Simultaneous measurements were made of laryngeal air resistance using the indirect technique so that the validity of this technique could be determined.

Airflow resistance, like electrical resistance, is not directly measured but rather is calculated from the quotient of the air pressure drop across the glottis and the airflow (4):

(resistance = air pressure/airflow).

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The denominator in this equation, airflow, can be easily measured during speech. The value used for the numerator should ideally be the difference between the subglottic air pressure and the supraglottic air pressure. However, since supraglottic air pressure is close to atmospheric air pressure during speech, the numerator can be approximated as the subglottic air pressure. Measurement of subglottic air pressure is usually accomplished with either a transcutaneous puncture of the cricothyroid membrane or intranasal passage of a transducer through the anesthetized vocal folds. Both of these procedures are invasive and uncomfortable for the subject. This has led to the development of a noninvasive or indirect method for measurement of subglottic air pressure.

The indirect method of laryngeal airway resistance uses intraoral air pressure to estimate subglottic air pressure. The subject is typically asked to speak a syllable beginning with a plosive consonant. A mask is placed over the subject's face to measure airflow. Intraoral air pressure is measured using a small catheter that passes through the face mask and into the subject's mouth. During the initial portion of the plosive consonant, the lips are closed and the glottis is open, so intraoral air pressure is considered equal to subglottic air pressure. Laryngeal airway resistance is calculated by dividing the peak intraoral air pressure immediately preceding the lip release by the airflow during the voiced segment. In many cases, the calculation is made only at the midpoint of the voiced segment. Since airflow and air pressure are measured at two different points in time, the assumption of constant subglottic air pressure is essential for the validity of the indirect technique.

The assumption that subglottic air pressure is unchanged throughout the voiced segment may not be valid in individuals with SD. If subglottic air pressure does vary during the voiced portion of the speech segment, laryngeal airway resistance measurements based on the intraoral air pressure are not valid. In this study we therefore simultaneously measured subglottic air pressure, airflow, and intraoral air pressure during speech in normal subjects and in subjects with SD.

BACKGROUND

Early studies (Ladefoged and McKinney) indirectly measured subglottic air pressure in three subjects using intraesophageal pressure measurements as a substitute for true subglottic air pressure (5). However, Kunze has shown that, under dynamic conditions, intraesophageal pressure cannot be used as a substitute for intratracheal or subglottic air pressure (6). Most studies investigating the validity of the indirect technique for LAR calculation have therefore relied on direct measurement of subglottic air pressure.

Shipp and McGlone performed simultaneous measurements of laryngeal electromyography (EMG) activity, airflow, subglottic air pressure, and fundamental frequency in 14 normal adult males (7). Subglottic air pressure was measured by inserting a 20 cm polyethylene tube into the trachea (the method of insertion was not described) and connecting the proximal end of the tube to a pressure transducer. Measurements were made during phonation at different frequencies. Subglottic air pressure was noted to rise with increased fundamental frequency, but measurements were made only at a single point in time during the voiced segment.

McGlone and Shipp also measured subglottic air pressure in 10 subjects as they spoke the consonants /p/ and /b/ (8). Air pressure was measured at two points in time: immediately prior to lip opening and at the point of maximum airflow following consonant release. The difference in air pressures between the two consonants was not significant. The air pressure at the point of maximum airflow was less than the air pressure immediately prior to lip opening, but this difference also was not significant. Subglottic air pressure was not measured during the voiced segment.

Smitheran and Hixon present data which they state strongly support the reliability of the indirect technique for measuring laryngeal air resistance (9). However, in their study they made no measurement of subglottic pressure and therefore never determined the actual laryngeal air resistance in any of their subjects. Validation of the indirect technique was based on comparison of the overall average laryngeal air resistance from 15 subjects with three previous studies (two of which are unpublished). In their study they never confirmed that subglottic air pressure remained constant in time nor did they assume any subject-to-subject variability in subglottic air pressure or laryngeal air resistance.

Netsell compared subglottic and intraoral air pressure associated with the consonants /t/ and /d/ in three normal adult males (10). Air pressure was measured via direct percutaneous puncture of the trachea between its first and second ring. Measurements were made at the time of tongue-alveolus contact and release for both consonants. Intraoral and subglottic air pressures were similar for both consonants at these two points in time, but no measurements were made during the voiced portion of the syllable.

Löfqvist, Carlborg, and Kitzing examined subglottic air pressure by transnasally passing a miniature air pressure transducer into the trachea (11). Intraoral and subglottic air pressure were compared for the voiceless stop /p/ followed by a vowel. A single subject, one of the authors, was studied. Air pressure was measured only at the midpoint of the voiced segment. The subglottic air pressures at this one point in time correlated well with intraoral air pressure during the closure period of the voiceless stop /p/.

Kitajima and Fujita measured intraoral and subglottic air pressure in seven subjects with tracheotomies (12). Three individuals had undergone partial laryngectomy, two had unilateral vocal fold paralysis, and two had normal larynges but had received a tracheotomy for other reasons. Subglottic air pressure was measured immediately prior to and immediately after the closure period of the voiceless stop /p/. Good correlation was seen with intraoral air pressure during those times. However, air pressure measurements were not made during the voiced segment following the /p/ and normal subjects were not studied.

Bard et al. used percutaneous puncture of the cricothyroid membrane to measure subglottic air pressure in two normal subjects speaking the syllable /pi/ (13). Good correlation was noted between subglottic air pressure prior to lip occlusion and oral cavity air pressure during occlusion. However, subglottic air pressure was not measured during the voiced portion of the syllable.

Hertegård, Gauffin, and Lindetad compared peak intraoral and peak subglottic air pressure in a single subject (14). Air pressure was measured during repeated /pa/ syllables via a 1.5 mm cannula percutaneously placed into the trachea. Subglottic air pressure at the midportion of vowel in this subject correlated well with peak intraoral air pressure. Measurements of subglottic air pressure during the voiced segment were not described.

Recent studies by McHenry et al. have shown discrepancies in the indirect method of laryngeal airway resistance measurement (15). Eight normal subjects were asked to speak in normal and abnormal voices. Air pressure was only recorded at the midvocalic point. Indirect airway resistance measurements were found to differ most with direct measurements in strained voices for females, and in breathy voice conditions for both males and females.

Measurements of subglottic air pressure in two adults with SD were made by Shipp et al. (1). In one of these individuals the subglottic air pressure was derived from intraesophageal balloon air pressures. Measurements for the second subject were made using a 20 cm tube placed into the trachea. Subglottic air pressure was measured as the subjects read a sentence containing only voiced segments. Average subglottic air pressures for these subjects during normal speech were 12.0 and 13.5 cm H_2O. These air pressures were approximately twice those reported in normal subjects. Perturbations in subglottic air pressure were seen in both subjects, a finding not felt present in normal subjects. Airflow was not measured so laryngeal airway resistance could not be calculated.

Finnegan et al. have shown that the variance in airflow is greater in SD than in normal subjects and speculate that variations may also be seen in subglottic air pressure of SD patients (2).

These studies showed that intraoral air pressure very nearly equaled subglottic air pressure during the period when the lips were closed. However, in many cases subglottic air pressure was not measured during the voiced portion of the syllable. In those studies in which subglottic air pressure was measured during speech, only a single point in time was studied. Consequently, the changes in subglottic air pressure during the voiced segment were not studied. Since the validity of the indirect technique for LAR measurement absolutely requires that subglottic air pressure remains constant, these previous studies never tested this crucial assumption. In this study subglottic air pressure was continuously measured as a function of time using percutaneous puncture of the cricothyroid membrane throughout the entire syllable. Intraoral air pressure and airflow were also simultaneously measured in all subjects so that laryngeal airway resistance could be calculated using both the indirect and the direct technique; therefore the results of the two techniques could be compared.

METHOD AND MATERIALS

The study group consisted of seven patients with SD enrolled in the Voice Disorders Clinic at the University of Washington and seven healthy volunteers. The normal subjects were nonsmokers with no previous history of neurological, laryngeal, or other voice disorder. The SD subjects had been diagnosed based on history, videostroboscopic exam, and laryngeal fine wire EMG. All SD subjects had previously been treated with Botox and measurements for this study were made immediately prior to one of their follow-up injections. Measurements were made in agreement with the provisions of the Human Subject Committee at the University of Washington .

Direct subglottic air pressure measurements were made by inserting a 21 gauge needle into the trachea through the cricothyroid membrane. The needle was connected via a 5 cm section of arterial tubing to an Omega PX186 air pressure transducer (Stamford, CT).

The time response of this air pressure measurement system was determined by measuring its response to a step function. This was accomplished by rapidly inserting and then removing the needle from a luer-lock injection port connected to a reservoir with an air pressure of approximately 80 cm H2O. Fig. 1 shows the decrease in air pressure as a function of time following removal of needle from a high-pressure reservoir, plotted on a logarithmic scale. Air pressure change as a function of time could be modeled as an exponential decrease:

$$P(t) = P_0 \exp(-kt),$$

The time constant calculated for the system with the 21 gauge needle (1/k) was 3.6 msec. A similar time constant was calculated for positive air pressure changes.

Airflow was measured using an airflow transducer (Hans Rudolph Inc., Kansas City, MO, 4719 Series). A tight mask was placed over the subject's face and air was directed through the transducer during speech.

An 8 cm section of arterial tubing was threaded through the face mask and into the subject's mouth. The distal end of the tube was positioned superior to the tongue. The proximal end of the tubing was connected to an Omega PX186 pressure transducer for measurement of intraoral air pressure.

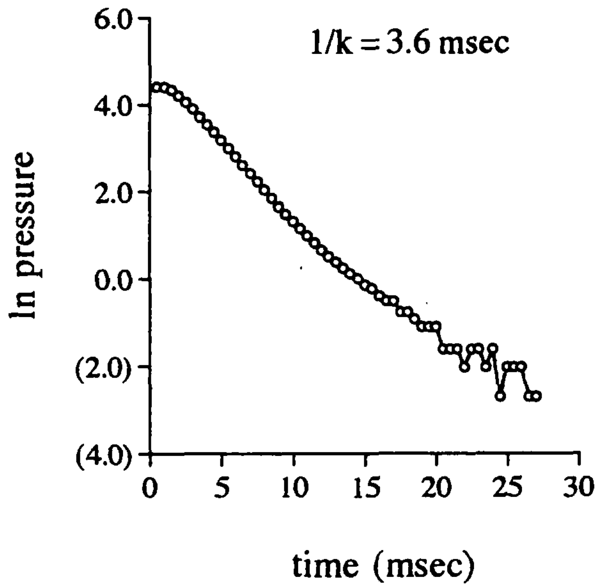


FIG. 1. Time response of the pressure measurement system.

All transducers were calibrated prior to each measurement. The pressure transducers were calibrated using a manometer set at 20 cm H2O. The flow meter was calculated using a known flow source of 500 cc/sec (Glottal Enterprises).

The subjects were placed in a reclining chair and approximately 0.1 cc of 1% lidocaine was infiltrated into the skin overlying the cricothyroid membrane. No anesthetic was placed into the trachea. The needle was advanced into the trachea and its position confirmed by asking the subject to perform a valsalva maneuver. The subjects were asked to phonate the syllable /pa/ at a rate of approximately 1.5-2.0 syllables per sec. Subglottic air pressure, intraoral air pressure, and airflow were sampled at 2000 Hz at 12-bit resolution and directly stored in a computer data file. Several of the subjects were also asked to phonate the syllable /pa/ and to maintain the vowel segment for several seconds.

Small periodic high-frequency variations were seen in all three signals. To remove these high frequency components the signals were low-pass filtered at 100 Hz using a 63-pole digital filter (Zola Technologies, Atlanta, GA).

RESULTS

A total of 60 tokens were analyzed in the seven normal subjects (the number of tokens per subject ranged from 4 to 15) and 47 tokens in the subjects with SD (tokens per subject ranged from 4 to 9). The relationship between subglottic air pressure at peak intraoral air pressure at completion of lip closure for all tokens is shown in Fig. 2. The intraoral air pressure at lip opening correlated well with subglottic air pressure at this point in time.

Fig. 3 shows examples of representative tracings from one of the normal subjects. In Fig. 3A, airflow, subglottic air pressure, and intraoral air pressure are shown as a function of time for a single token. In this example, intraoral air pressure and subglottic air pressure both simultaneously rose during the initial portion of the consonant. At the moment of lip opening, intraoral air pressure rapidly dropped and airflow rapidly increased to peak values. Airflow then decreased and remained fairly constant during the voiced portion of the syllable.

Fig. 3B shows laryngeal airway resistance as a function of time for this token. The resistance has been calculated using both the direct (dotted line) and the indirect technique (dashed line). The pressure used for the indirect laryngeal airway resistance calculations was based on an interpolation of the line connecting two successive intraoral air pressure peaks. In this case subglottic air pressure remained fairly constant during the voiced segment, so the indirect technique produced a valid estimate of true laryngeal airway resistance.

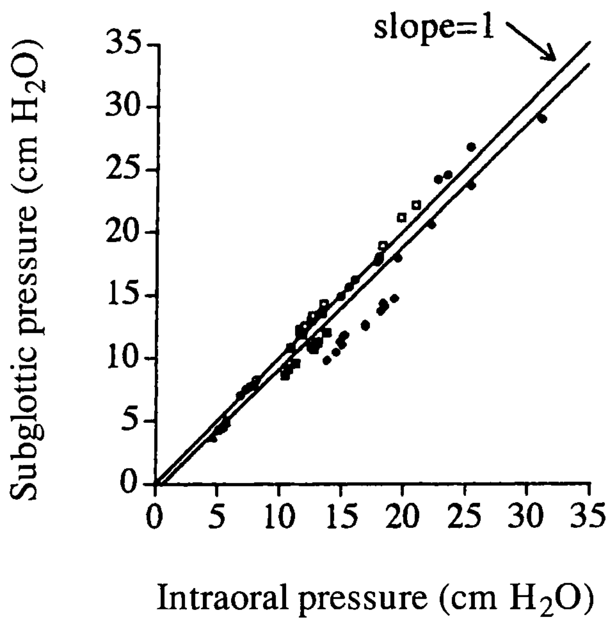


FIG. 2. Correlation between subglottic and intraoral air pressure at the time of lip opening, all subjects.

Two of the seven normal subjects had subglottic air pressures that remained fairly constant during the voiced portion of the syllable. However, an unexpected decrease in subglottic air pressure was observed in five of the seven normal subjects. Fig. 4 shows a series of syllables from one of these subjects. Instead of remaining constant, the subglottic air pressure decreased during each of the voiced segments of the syllable.

A closer examination of this pattern is shown in Fig. 5, taken from another normal subject. In this case both airflow and subglottic air pressure slowly decreased during the voiced segment (Fig. 5A). The true laryngeal airway resistance therefore remained constant. However, the indirect method of laryngeal airway resistance calculated a slow increase in laryngeal airway resistance since it did not take into account the decrease in subglottic air pressure (Fig. 5B).

A more dramatic example of change in subglottic air pressure is seen in Fig. 6, measured in the same normal subject. The subglottic air pressure continued to rise after lip release, with a final peak 65% higher than the peak intraoral air pressure. After reaching this peak the subglottic air pressure fell quite rapidly during the voiced segment. Near the end of the syllable it had fallen to less then 50% of peak subglottic air pressure. Airflow also fell during the segment, but not as quickly as the subglottic air pressure.

Fig. 6B shows the impact these findings had on the calculation of laryngeal airway resistance. Since the airflow decreased during the token, the indirect technique mistakenly concluded that laryngeal airway resistance had increased. Instead, the subglottic air pressure fell more rapidly than the airflow, so true laryngeal airway resistance actually decreased.

For subjects with SD, the most pronounced findings noted were large variations in airflow and, in some cases, increased subglottic air pressure. An example of an individual with mild SD is shown in Fig. 7. Both airflow and subglottic air pressure showed

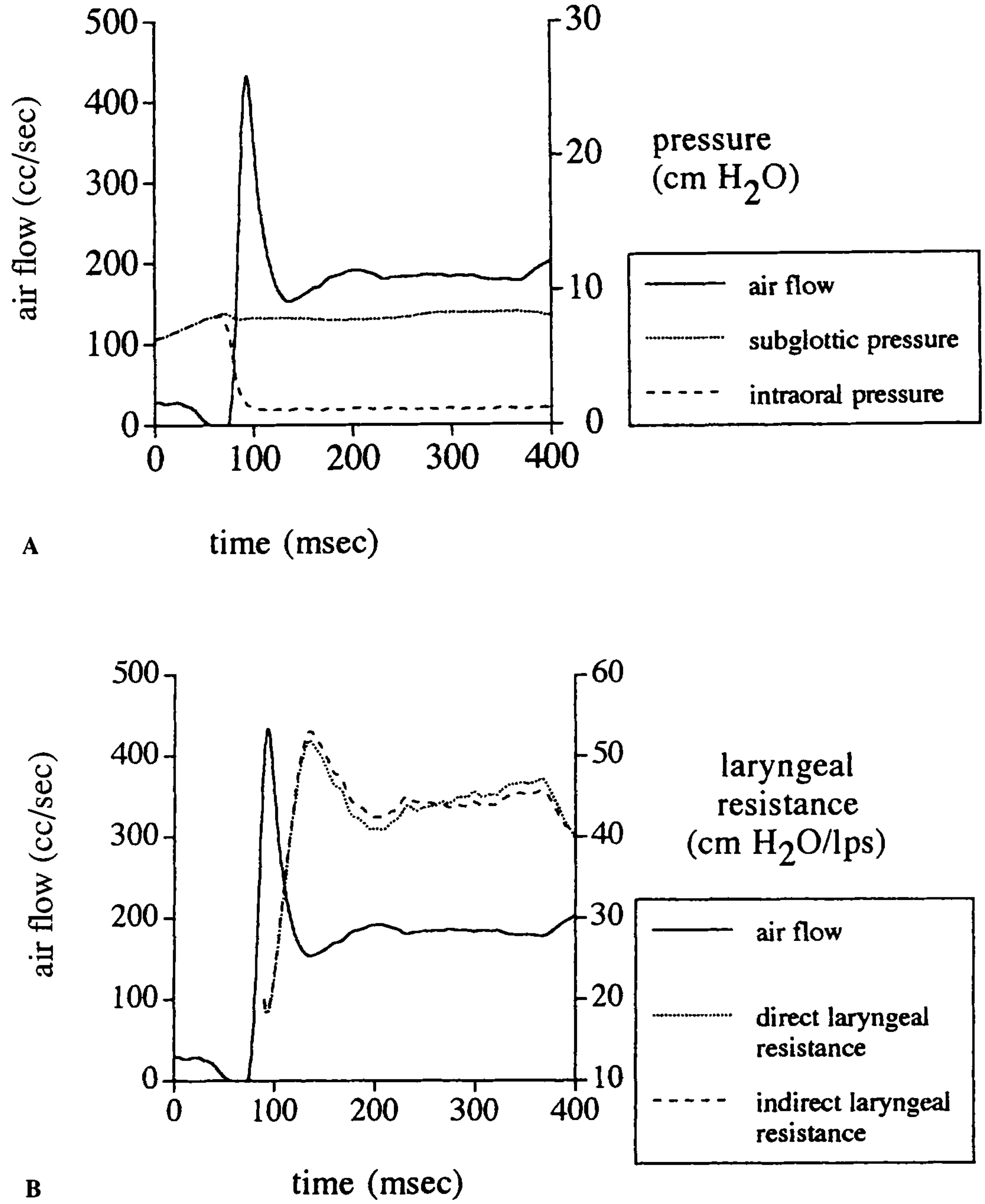


FIG. 3. A. Airflow, subglottic pressure, and intraoral air pressure in one syllable from a normal subject. **B.** Airflow and laryngeal airway resistance calculated using the direct and the indirect technique for this syllable.

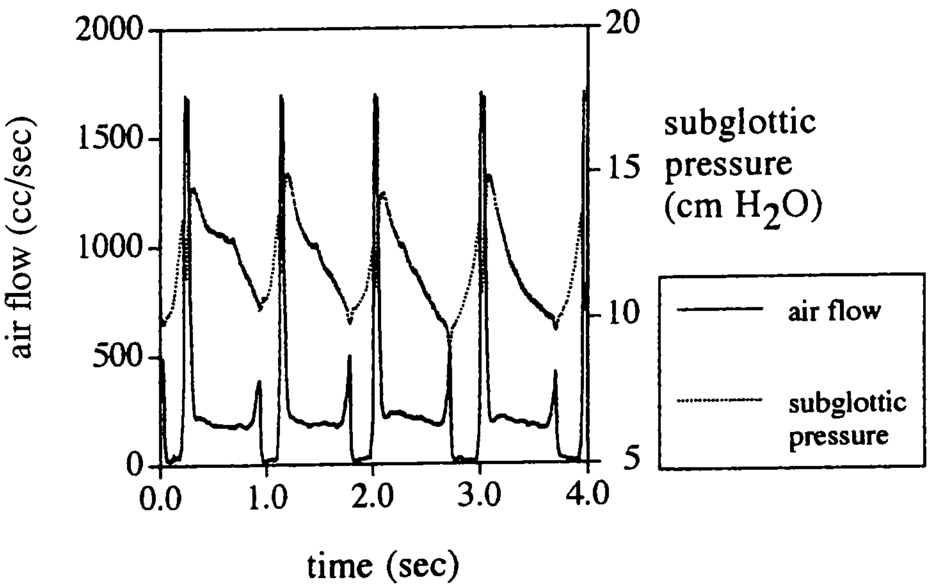


FIG. 4. Air flow and subglottic air pressure during a series of syllables from a normal subject. Subglottic air pressure can be seen to fall during the voiced portion of the syllable.

gradual fluctuations over time (Fig. 7A). Although the overall changes were not large, decreases in airflow did correspond with increases in subglottic air pressure (Fig. 7B). Laryngeal airway resistance fell throughout the voiced segment except for momentary increases during pitch breaks.

Fig. 8 shows an example of a subject with more severe SD. In this case there were near-complete breaks in airflow. Subglottic air pressure was much higher than normal, but showed minor changes during the pitch breaks (Fig. 8A). Laryngeal resistance rapidly increased with each break as air flow approached zero (Fig. 8B).

Changes in subglottic air pressure were quantified by comparing the peak subglottic air pressure reached during the voiced segment with the air pressure at the midpoint and at 100 msec after the midpoint of the segment. These results are shown in Table 1. Also shown is the rate of change in subglottic air pressure in the 100 msec following the midpoint. In five of the seven normal subjects the air pressure had dropped to less than 71% of the peak air pressure just 100 msec after the midpoint. In one subject the subglottic air pressure had fallen by nearly 50% from peak levels. Moreover, air pressure was falling at this time at 11 to 30 cm H2O/sec in these same subjects.

Similar results are shown for the SD subjects in Table 2. Subglottic air pressure decreased during the voiced segment for these subjects as well, though the decreases were not as great. The rates of change of the subglottic air pressure were less than seen in the normal subjects.

Laryngeal airway resistance was calculated, using the direct technique, at the midpoint of the syllable and 100 msec after the midpoint in the normal subjects. The averages for these subjects are shown in Table 3. The laryngeal airway resistance decreased for all subjects during the voiced segment, though in several cases the decrease was 10% or less. As subglottic air pressure fell, there often was a corresponding drop in laryngeal airway resistance enabling airflow to remain more constant.

In order to compare the direct and indirect techniques, average laryngeal airway resistance was calculated using each method for a 200 msec time period centered around the midpoint. The averages are shown in Table 4. The discrepancy between the true laryngeal airway resistance measured directly in the resistance calculated with the indirect technique varied from −44% to +50%.

In most cases the indirect technique overestimated the true laryngeal resistance. This overestimation occurred because subglottic air pressure fell during the

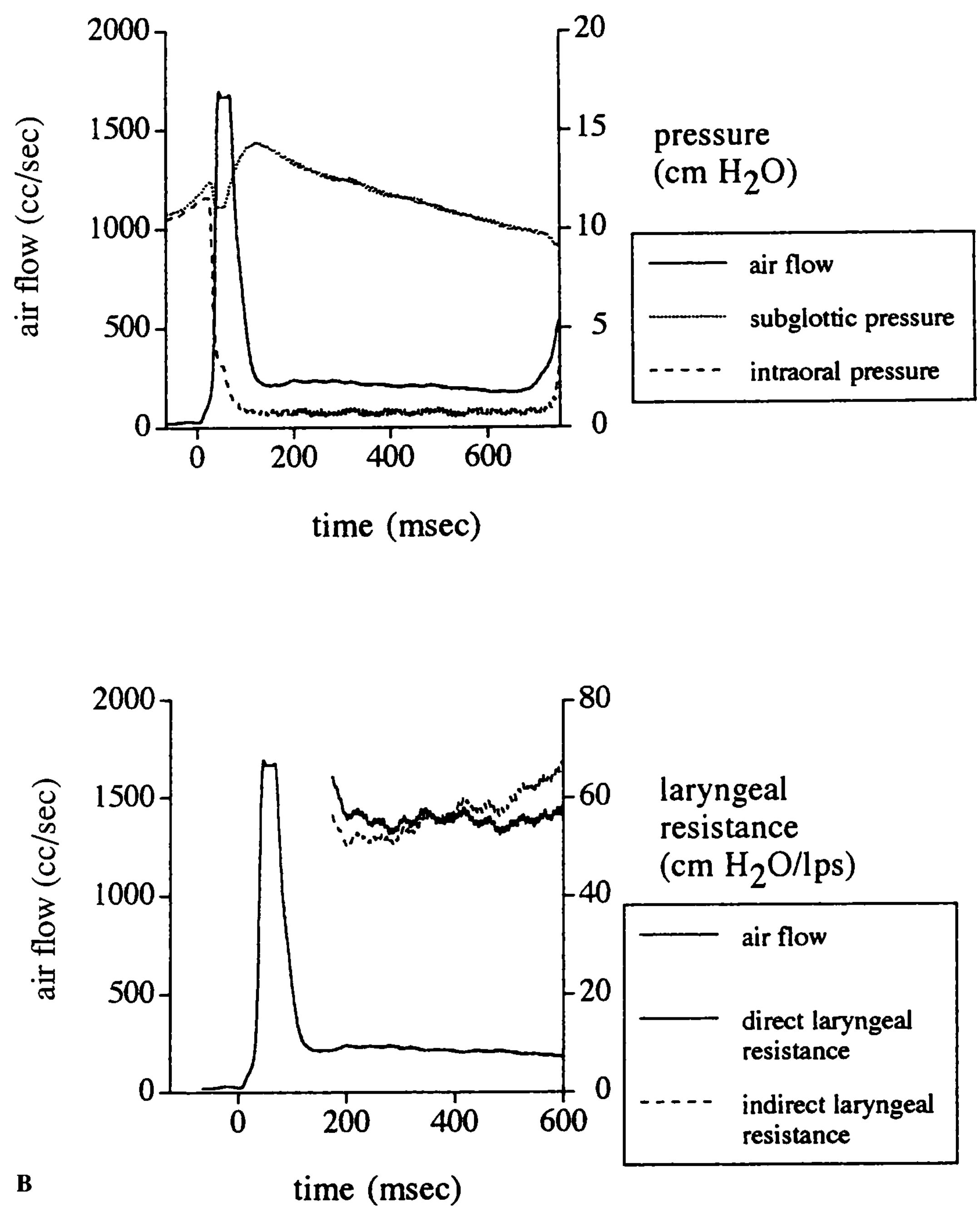
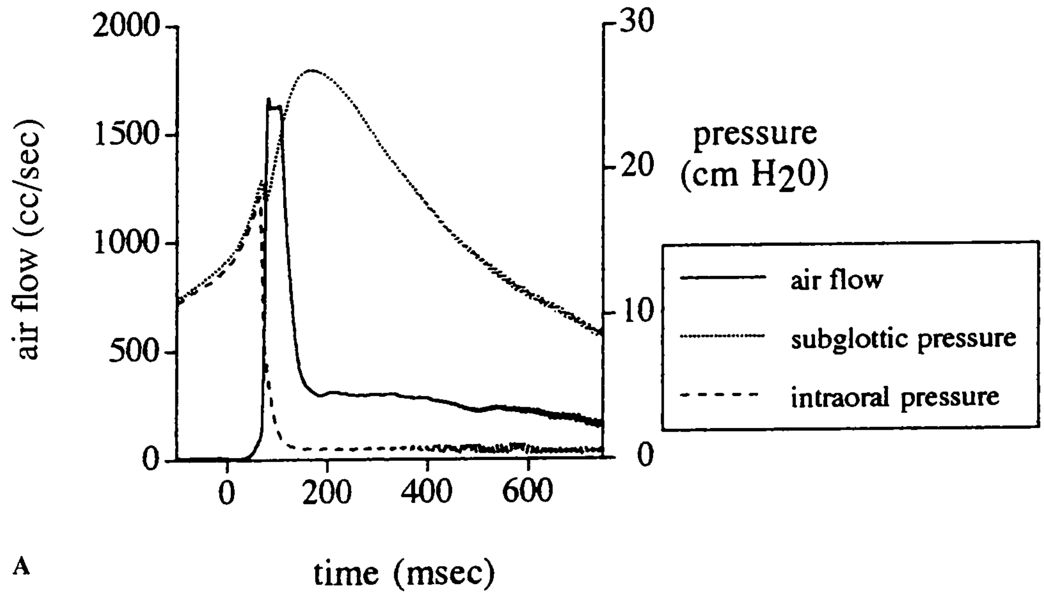


FIG. 5. A. Airflow, subglottic pressure, and intraoral pressure in one syllable from a normal subject. Unlike Fig. 3A, subglottic air pressure decreased during the syllable. **B.** Airflow and laryngeal airway resistance calculated using the direct and the indirect technique for this syllable.



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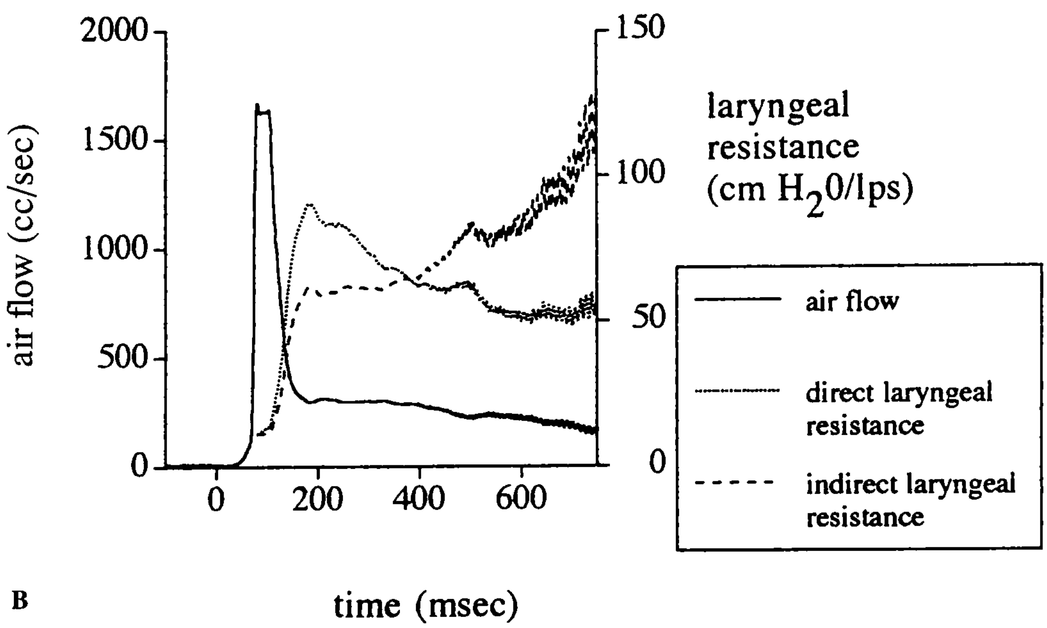

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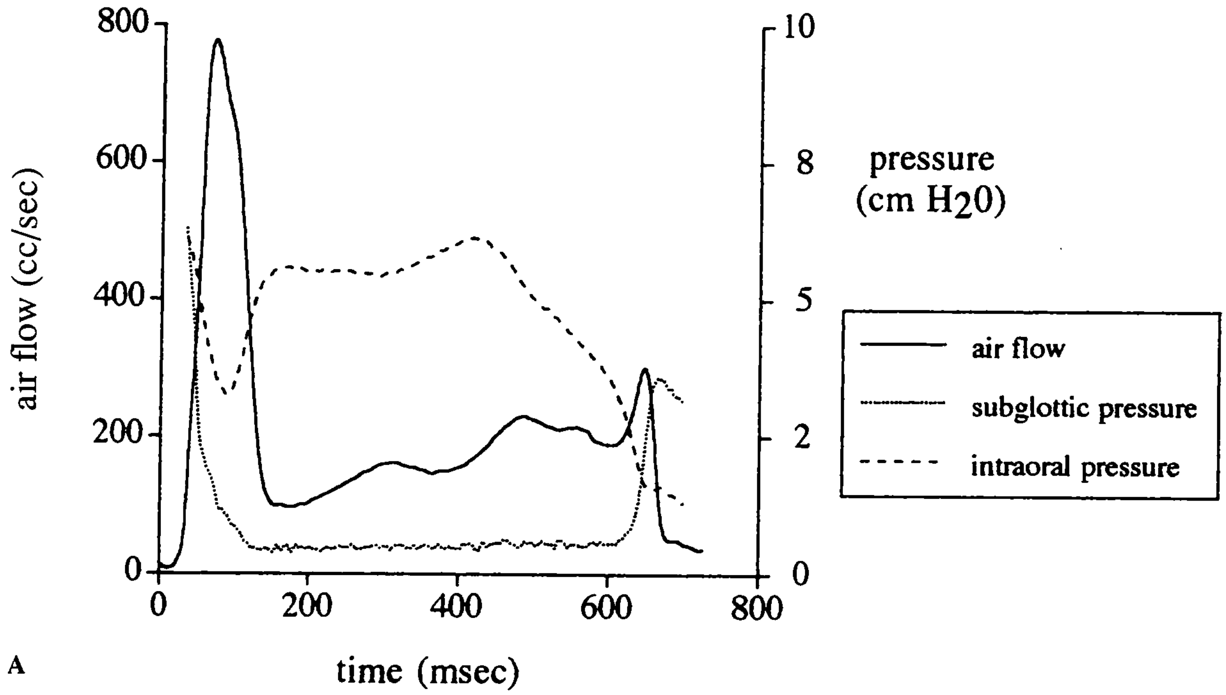
FIG. 6. A. Airflow, subglottic air pressure, and intraoral air pressure in one syllable from a normal subject. Subglottic air pressure rose after lip opening and then fell by more than 50% from peak values. **B.** Airflow and laryngeal airway resistance calculated using the direct and the indirect technique for this syllable. The indirect method produced incorrect values due to its assumption of constant subglottic air pressure.



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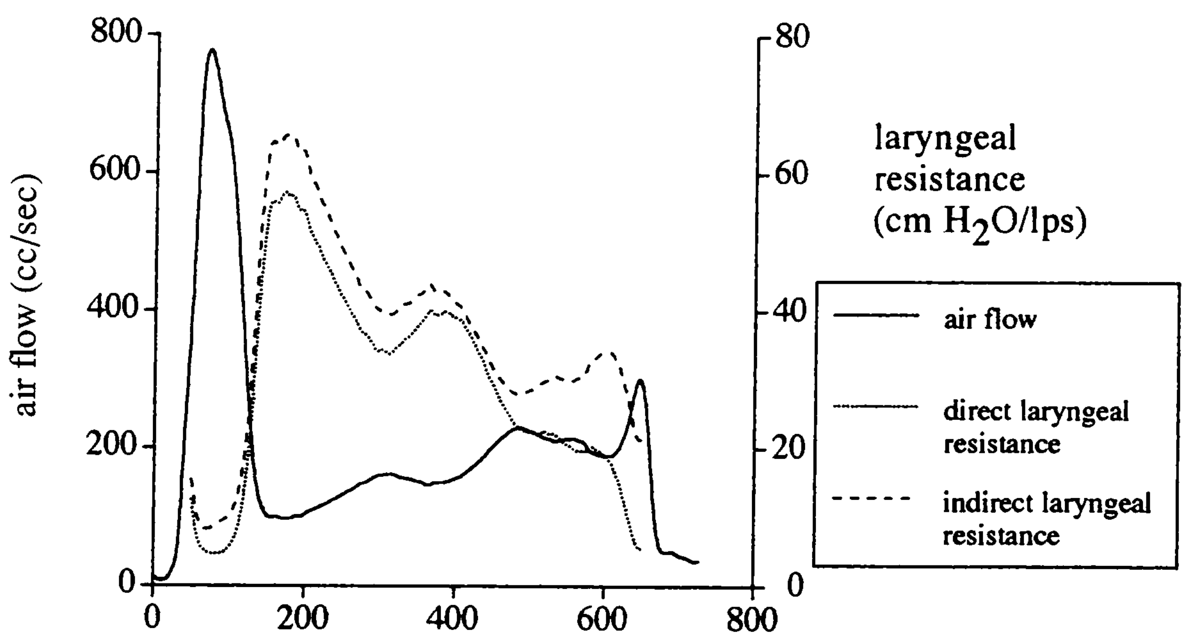

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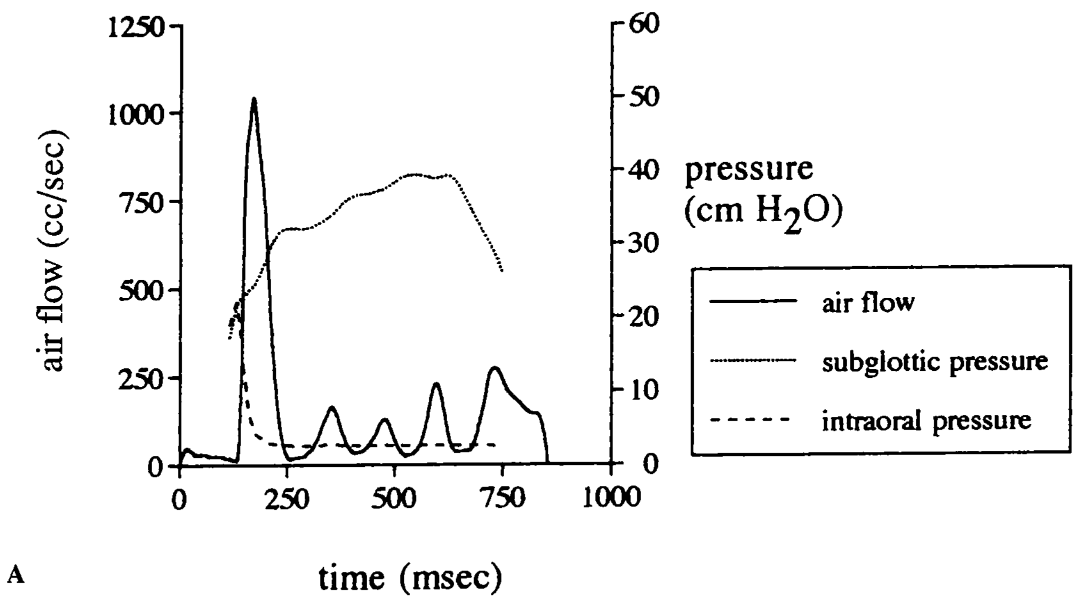
FIG. 7. A. Airflow, subglottic air pressure, and intraoral air pressure in one syllable from an SD subject. **B.** Airflow and laryngeal airway resistance calculated using the direct and the indirect technique for this syllable.



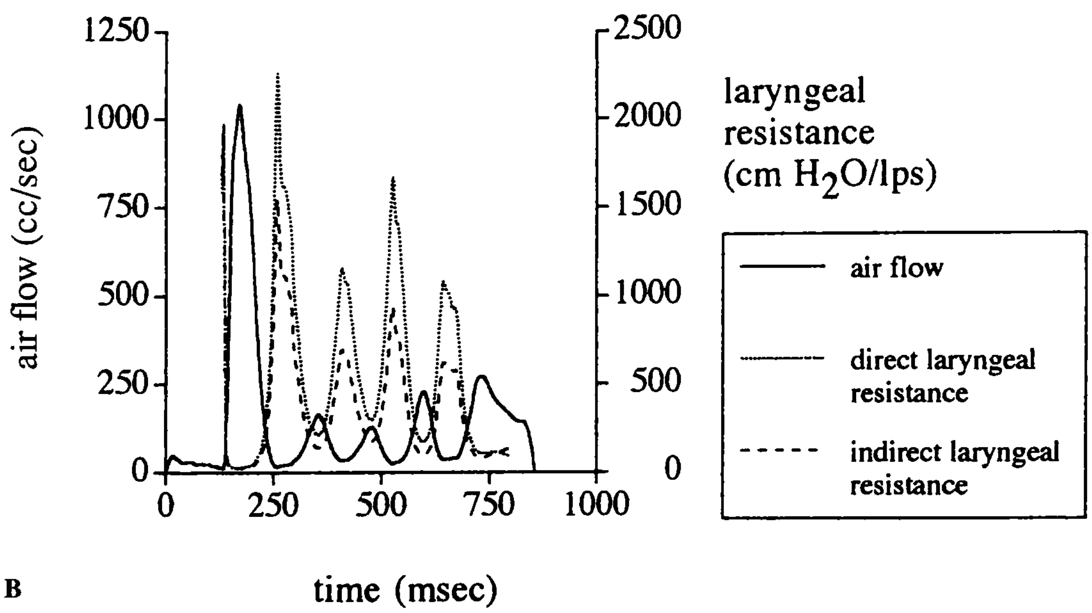


FIG. 8. **A.** Airflow, subglottic air pressure, and intraoral air pressure in one syllable from a subject with severe SD. **B.** Airflow and laryngeal airway resistance calculated using the direct and the indirect technique for this syllable.

TABLE 1. *Subglottic pressure (cm H_2O) measured during the voiced portion of the syllable in normal subjects*

Subject	Peak	Midpoint	Rate of pressure change Midpt 1 100 mscec	(cm H_2O/sec)
MW	17.5	11.0 (0.67)	9.6 (0.55)	−13.4
MN	22.8	15.8 (0.71)	14.7 (0.64)	−11.2
JB	8.7	8.6 (0.98)	6.2 (0.71)	−23.7
JL	9.3	8.6 (0.93)	8.0 (0.85)	−7.0
BP	11.5	8.4 (0.74)	7.2 (0.63)	−12.4
BB	13.4	11.3 (0.84)	8.2 (0.61)	−30.8
LB	17.6	17.2 (0.97)	16.7 (0.95)	−5.0

Note: The table shows the peak pressure, the pressure at the midpoint of the voiced segment, and the pressure 100 ms after the midpoint. The figures in parentheses represent the value of the pressure relative to the peak subglottic pressure during the syllable. The final column shows the rate of change in the 100 ms following the peak.

TABLE 2. *Subglottic pressure (cm H_2O) measured during the voiced portion of the syllable in subjects with SD*

Subject	Peak	Midpoint	Rate of pressure change Midpt 1 100 mscec	(cm H_2O/sec)
AZ	9.6	8.9 (0.93)	8.1 (0.84)	−8.4
IG	10.9	10.6 (0.97)	10.1 (0.92)	−4.6
KR	6.1	5.5 (0.90)	4.9 (0.80)	−5.9
LK	8.1	6.5 (0.81)	6.3 (0.79)	−4.4
SA	9.5	9.1 (0.96)	8.5 (0.90)	−12.8
VV	8.3	7.7 (0.93)	5.7 (0.68)	−20.3
NY	38.8	38.2 (0.98)	38.4 (0.99)	+2.0

Note: The table shows the peak pressure, the pressure at the midpoint of the voiced segment, and the pressure 100 ms after the midpoint. The figures in parentheses represent the value of the pressure relative to the peak subglottic pressure during the syllable. The final column shows the rate of change in the 100 ms following the peak.

voiced segment below the level of intraoral air pressure measured at time of lip opening. In two subjects the average subglottic air pressure rose after lip opening, and in these cases the indirect technique underestimated the true laryngeal airway resistance.

The same comparison for SD subjects is shown in Table 5. Due to the high variability of laryngeal airway resistance in SD subjects, comparisons based on average values may be less useful. Since subglottic air pressure showed gradual decreases over time in SD subjects, one would have expected the indirect technique to again overestimate average laryngeal airway resistance. Instead, there was a trend to underestimate the resistance, apparently due to increases in subglottic air pressure that exceeded the original intraoral air pressure.

COMMENTS

The indirect technique for measurement of laryngeal airway resistance has two major limitations: (1) intraoral air pressure is measured instead of subglot-

TABLE 3. *Direct measurement of laryngeal airway resistance (cm H2O/(liters/sec)) in normal subjects at two points in time during the voiced portion of the syllable*

Subject	Midpoint	Midpoint + 100 msec	Percent change
MW	57.4	54.9	−4%
MN	75.8	68.6	−9%
JB	45.9	19.7	−57%
JL	46.1	38.9	−16%
BP	36.4	32.8	−10%
BB	31.1	25.4	−18%
LB	101.2	100.0	−1%

TABLE 4. *Comparison of direct and indirect techniques for calculating laryngeal airway resistance in normal subjects*

Subject	Direct technique	Indirect technique	Error in indirect technique
MW	57.9	72.2	+25%
MN	77.4	109.8	+41%
JB	40.0	36.4	−9%
JL	44.8	25.1	−44%
BP	37.0	52.4	+42%
BB	30.7	46.0	+50%
LB	103.3	115.8	+12%

TABLE 5. *Comparison of direct and indirect techniques for calculating laryngeal airway resistance in subjects with SD*

Subject	Direct technique	Indirect technique	Error in indirect technique
AZ	113.1	99.5	−12%
IG	223.7	158.6	−29%
KR	30.2	33.3	+10%
LK	62.1	75.5	+22%
SA	310.2	235.9	−24%
VV	63.4	53.1	−16%
NY	1030.2	523.2	−49%

tic air pressure, and (2) the air pressure and the airflow are measured at different points in time. In order for this technique to be valid, one must assume that the intraoral air pressure equals the subglottic air pressure at the time of lip opening, and that the subglottic air pressure remains constant in time. Under these circumstances, laryngeal airway resistance varies as the inverse of the airflow.

This present work has expanded on previous studies through its use of a direct invasive technique in a larger sample size of normal and SD subjects, and its emphasis on measurement of subglottic air pressure throughout the entire syllable. Most previous studies concentrated only on the period of lip closure and made few measurements during the voiced portion of the syllable. Many of the studies also had small sample size, with three subjects or less.

Our original hypothesis was that indirect air pressure techniques would not be valid in SD due to variations in subglottic air pressure. Large variations in subglottic air pressure were unexpectedly seen in five of our seven normal subjects. In these subjects, subglottic air pressure had decreased by 29% or more from peak values just 100 msec after the midpoint of the voiced segment.

In two normal subjects the subglottic air pressure rose after initial lip separation so that subglottic air pressure, for a short time, exceeded intraoral air pressure. The air pressure then fell during the remainder of the voiced segment, occasionally by as much as 30 cm H_2O/sec. At the midpoint, the combination of the initial jump in air pressure followed by a steady decrease produced a subglottic air pressure that roughly equaled the original intraoral air pressure. If subglottic air pressure had only been measured at this point, as many previous studies have done, one could mistakenly conclude that subglottic air pressure had not changed. In reality, the air pressure often was rapidly decreasing at that point in time.

Since subglottic air pressure was not constant during the speech segment, indirect measurements of laryngeal airway resistance produced misleading results. The indirect technique tended to overestimate the laryngeal resistance in normals because it did not take into account the decrease in subglottic air pressure. In subjects with SD it tended to underestimate the laryngeal airway resistance, since subglottic air pressure often rose after initial lip opening. The difference between the actual average laryngeal resistance and the resistance measured indirectly ranged from −44% to +50% in normal subjects, and from −49% to +22% in SD subjects.

These results emphasize above all the importance of continuous measurement of subglottic air pressure for accurate determination of laryngeal airway resistance. It is not sufficient to measure subglottic air pressure only at the time of lip separation or at the midvocalic point. During lip occlusion, intraoral air pressure does equal subglottic air pressure. However, after lip separation and during the voiced segment the subglottic air pressure does not remain constant in all cases. This was noted despite a wide variety of intraoral air pressures and airflow rates for the speakers. The true laryngeal resistance can therefore only be determined if subglottic air pressure is directly measured using placement of a transducer probe into the subglottic space.

One might expect that subglottic air pressure would be unstable in SD subjects due to spasms in the vocal folds. Several of the SD subjects did show slight increases in subglottic air pressure during pitch breaks, but the increases were much less than expected. Subglottic air pressure generally tended to decrease during the voiced portion of the syllable for most of the SD subjects, but the decreases were not as large as those observed in the normal subjects.

Laryngeal airway resistance was substantially higher in SD than in the normal subjects. The increased laryngeal airway resistance was demonstrated primarily as lower rates of airflow. The laryngeal airway resistance also showed rapid increases during pitch breaks. These pitch breaks were associated with rapid decreases in airflow, but with relatively minor changes in subglottic air pressure. Laryngeal airway resistance was therefore influenced more by changes in airflow than by changes in subglottic air pressure.

CONCLUSION

Indirect and direct continuous measurement of laryngeal airway resistance has been performed during syllable production in normal subjects and in subjects with SD. Subglottic air pressure during the voiced segment of the syllable was not constant in five of the seven normal subjects, but instead decreased by 29% or more. In SD subjects the subglottic air pressure often rose to levels that exceeded the peak intraoral air pressure. Due to these and other changes in subglottic air pressure during speech, the error in the indirect method for laryngeal airway resistance measurement ranged from −44% to +50% in the normal subjects and from −49% to +22% in the SD subjects. In general, the indirect technique tended to overestimate laryngeal airway resistance in normal subjects and underestimate the resistance in SD subjects.

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