A CLINICAL METHOD FOR ESTIMATING LARYNGEAL
AIRWAY RESISTANCE DURING VOWEL PRODUCTION

by

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ABSTRACT

A noninvasive clinical method for estimating laryngeal airway resistance during vowel production is described. Resistance is calculated as the ratio of translaryngeal pressure to translaryngeal flow, the first determined from measurement of oral pressure and the second determined from measurement of airway-opening flow made during the utterance of a specially-designed speech sample. Application of the method to the study of vowel utterances of 15 normal adult males resulted in a calculated mean laryngeal airway resistance of 35.7 cm H₂O/LPS. This value is remarkably similar to those obtained in previous research using complex invasive experimental methods. Clinical use of the method is illustrated in case studies which highlight both evaluation and management potentials. It is concluded that the method proposed is clinically practical, that the data it provides are both valid and reliable, and that the method shows great promise of becoming a routine clinical tool for estimating laryngeal airway resistance during vowel production.

INTRODUCTION

The human larynx is an intricate mechanical valve situated between the lower and upper airways of the respiratory apparatus. Much can be inferred about the function of this valve during vowel production from knowledge of the magnitude of coupling it permits between the trachea and pharynx. Such knowledge can be obtained in different but related forms, one of the most pertinent of these being the extent to which the larynx offers opposition to the flow of air through it. In technical parlance, this opposition to flow is termed laryngeal airway resistance (R_{law}). Laryngeal airway resistance cannot be measured directly but must be calculated from the ratio of translaryngeal pressure (P_{tl}) (the difference between tracheal pressure and pharyngeal pressure) to translaryngeal flow ($\dot{V}_{tl}$) (the flow through the larynx). Restated, $R_{law} = P_{tl} / \dot{V}_{tl}$.

The clinical literature contains many statements concerning the relevance of information on laryngeal airway resistance during vowel production. This relevance is expressed mainly for three clinical endeavors: (1) the understanding of disordered function, (2) the evaluation of disordered function, and (3) the management of disordered

function. Unfortunately, current clinical technology does not enable the easy acquisition of data on laryngeal airway resistance. Clearly, the greatest difficulty in this regard has to do with the fact that the pressure in the trachea must be known to obtain the translaryngeal pressure data needed to calculate resistance. Continuous direct recording or continuous indirect estimation of this pressure requires one of the following: (1) that a sensing probe (catheter, hypodermic needle or miniature transducer) be positioned within the trachea (Van den Berg, 1956; Isshiki, 1964; Koike and Perkins, 1968), (2) that a sensing probe (catheter-balloon or miniature transducer) be positioned within the esophagus (Bouhuys, Proctor and Mead, 1966; Hixon, 1972), or (3) that the subject be encased in a whole-body chamber (Hixon and Warren, 1971). The first two approaches -- tracheal and esophageal probes -- are invasive, cause discomfort to the subject, place the subject at physical risk, and require the assistance of a physician. The third approach -- whole-body encasement -- requires plethysmographic systems that are rare, cumbersome, demand substantial technical sophistication, and call for the performance of complex calibration maneuvers by the subject.

This thesis reports on the development and testing of a new, simple, noninvasive clinical method for estimating laryngeal airway resistance during vowel production. This

method circumvents the need to base resistance determinations on data that include continuous direct recording or continuous indirect estimation of tracheal pressure. In the sections to follow, consideration is given to the conceptual development of the method, the salient features of the method, data obtained from use of the method on a group of normal subjects, and implications pertaining to the general clinical application of the method.

CONCEPTUAL DEVELOPMENT

As stated above, laryngeal airway resistance is calculated from the ratio of translaryngeal pressure to translaryngeal flow (repeating, $R_{law} = P_{tl}/\dot{V}_{tl}$). Three quantities must be known for this calculation to be made:

- (1) tracheal pressure, (2) pharyngeal pressure, and
- (3) translaryngeal flow.

The conceptual development of the present method has its roots in modern general theory of fluid dynamics. Such theory predicts that in many types of fluid-filled systems, certain combinations of valving adjustments make it possible to estimate upstream pressure-flow events from recordings of pressure-flow events made at sites that are substantially downstream of the measurement sites of interest. Upon application of this same theory to the air-filled respiratory airways, it becomes apparent that certain combinations of valving adjustments of the larynx, velopharynx, and oral segment make it possible to estimate tracheal pressure, pharyngeal pressure, and translaryngeal flow from recordings of pressure-flow events made downstream of the trachea, pharynx, and larynx. Furthermore, these very same combinations of valving adjustments are found to occur naturally in the aeromechanical valving scheme

associated with the use made of the respiratory airways during the production of certain speech-sound subsets within the English language.

Given the aeromechanical and phonetic realizations just mentioned, it becomes possible to combine these two areas of knowledge in a manner that permits the non-invasive determination of laryngeal airway resistance during vowel production. The key to this combining is the construction of an utterance sample, which, when elicited from a subject, calls up and serially orders various combinations of valving adjustments such that from the simultaneous and continuous recording of relevant downstream pressure-flow events, it is possible to make discontinuous estimates of tracheal pressure, pharyngeal pressure, and translaryngeal flow associated with the vowel elements contained within the utterance sample.

The simplest of potential utterance samples in this regard are those which repeatedly alternate segmentally between voiceless stop-plosives and voiced vowels. These two types of segments are characterized by different combinations of valving adjustments. In the case of the voiceless stop-plosive, two sets of adjustments occur: an initial set constituting a "closed" phase and a final set constituting a "release" phase. The closed phase includes a combination of adjustments in which the laryngeal valve is

open and the velopharyngeal and oral valves are closed. The release phase, by contrast, includes a combination of adjustments that maintain an open laryngeal valve and a closed velopharyngeal valve, but which involve an abrupt opening of the oral valve. In the case of the voiced vowel, a single set of adjustments occurs. Production includes a combination of adjustments in which the laryngeal valve is relatively highly constricted on the average (through repeated passive opening and closing of the glottis at high speed), the velopharyngeal valve is closed, and the oral valve is open such that the oral airway is in a relatively unconstricted configuration.

When the type of utterance sample just mentioned is produced, two downstream variables -- oral pressure and airway-opening flow -- can be used as measurement substitutes for the critical upstream variables of tracheal pressure, pharyngeal pressure, and translaryngeal flow. Downstream oral pressure can be used to obtain discontinuous estimates of tracheal pressure and pharyngeal pressure at different moments during such an utterance sample, and downstream airway-opening flow can be used to obtain discontinuous estimates of translaryngeal flow.

Estimates of tracheal pressure can be obtained from the measurement of oral pressure by taking into account the following: for one instant during the production of a voiceless stop-plosive, oral pressure and tracheal pressure

are identical. This unique correspondence between oral pressure and tracheal pressure occurs during the closed phase of stop-plosive production when the upper airway is momentarily sealed airtight, except at its laryngeal entry. During the latter part of this closed phase of production, the pressure within the oral cavity behind the site of airway occlusion equilibrates with the pressure within the lower airways, trachea included. More specifically, this moment of oral-tracheal pressure equilibration is coincident with the occurrence of the peak oral pressure associated with the voiceless stop-plosive (Netsell, 1969; Shipp, 1973). Thus, the peak oral pressure during the production of a voiceless stop-plosive can be taken as an estimate of the tracheal pressure existing at the corresponding moment. In the case of the type of utterance sample discussed above -- one which repeatedly alternates between voiceless stop-plosives and voiced vowels -- it is possible to take advantage of the data provided in successive peaks of oral pressure to infer the overall tracheal pressure contour for the utterance. This can be done by linearly interpolating the pressure between adjacent oral pressure peaks (that is, between closed phases of adjacent consonants), and then constructing an underlying tracheal pressure contour from the successive linear interpolations. Through use of such a constructed underlying tracheal pressure contour, it is

then possible to estimate the tracheal pressure associated with vowel segments that fall between adjacent pairs of stop-plosive consonants.

Turning to the use of oral pressure to estimate pharyngeal pressure, attention focuses on a different moment during the production of the type of utterance sample that has been discussed. Specifically, estimates of the pharyngeal pressure associated with each vowel production can be obtained from the measurement of oral pressure made during each vowel within the utterance sample. The direct substitution of oral pressure for pharyngeal pressure is possible on vowel utterances because the pressure drop between the pharynx and the oral cavity is essentially nil during voiced vowel utterance, the oral airway being relatively unstricted and the flow through the same airway being relatively low. In fact, under most circumstances of normal vowel production, where flows through the upper airway are typically relatively low, one would sacrifice little precision in calculation of laryngeal airway resistance were pharyngeal pressure and oral pressure simply assumed to be zero.

The use of downstream airway-opening flow as a discontinuous estimate of translaryngeal flow is made possible because of the continuity of mass flow through the overall upper airway during the vowel segments of the type of utterance sample described above. Structural displacements

of the upper airway during vowel production (that is, articulatory motions) generate small flows, but these are trivial in comparison to the flow component related to air displacement through the larynx, and can be neglected.

In any event, the potential contribution of such "airway" flows is rendered zero if airway-opening flow measurements are made during moments when the airway adjustment for vowel production is in a quasi-static state, such as prevails during the middle portion of vowels produced in the type of utterance sample considered here.

METHOD

Introductory Comment

The method proposed evolved from an extensive pilot investigation that considered different utterance samples, equipment arrays, subject testing procedures, and data analyses. Seven normal adult males served as pilot subjects in one or more of the areas considered. In the subsections to follow, a fully-developed standard protocol is proposed for use in clinical situations. Where appropriate, this protocol is justified on pilot experiences. Subjects described in the next subsection are those for whom data are presented in the RESULTS section, and on whom the fully-developed protocol was tested once it was judged satisfactory.

Subjects

Fifteen adult males served as test subjects for the method. These individuals ranged in age from 21 years, 10 months, to 40 years, 6 months. Ages were distributed relatively evenly within this range. Subjects were selected to meet the following criteria: normal speech and voice commensurate with age, hearing reported to be within normal limits, no known structural or neurological disorders, and

no known respiratory infections or allergies at the time of testing. All subjects were monolingual, English-speaking Caucasians. Choice of the subject group was prompted by the desire to infer the validity of the present clinical method via comparisons of data from the present subjects and similar subjects studied by others with previous experimental methods.

Utterance Sample

Design of the utterance sample was guided by the desire to provide a task that met the following general considerations: (1) fulfilled the constraints imposed by the theory underlying the method; (2) was simple for subjects to perform and would have widespread clinical application to other subjects, including young children, difficult-to-test individuals, and persons with structural or neuromuscular disorders of the speech apparatus; (3) was of a character akin to conversational speech but controlled for variables that might influence resistance values; (4) would yield data that could be analyzed easily and quickly in a routine clinical operation; (5) minimized potential measurement artifacts associated with the method; and (6) minimized the complexity of subject-equipment interfacing.

The utterance sample employed was the syllable /pi/ repeated in three separate trains of seven productions each.

For each train, subjects were instructed to take a breath of about twice normal depth and to produce the seven productions on a single, continuous expiration, at normal loudness, pitch, and quality, with equal stress on each syllable, with each of the seven vowels in the train prolonged slightly, and at an utterance rate of 1.5 syllables per second (as paced externally). The rationale for the selection of these particular utterance sample features was based upon the considerations discussed below.

At the segmental level, the voiceless stop-plosive /p/ and the voiced vowel /i/ were the elements chosen for inclusion. The consonant /p/ offered the following merits for selection from among the three voiceless stop-plosive candidates in the English language (/p, t, k/): (1) it has been shown empirically that oral pressure and tracheal pressure equilibrate at the moment of occurrence of peak oral pressure during /p/ production (Shipp, 1973), so that /p/ meets one of the important central constraints imposed by the theoretical basis underlying the method; (2) it has been shown empirically that /p/ is the first of the voiceless stop-plosives to emerge in the ordered sequence of speech-sound development (Prather, Hedrick, and Kern, 1975), so that it may have the widest potential applicability in subject testing; (3) the place of production of /p/ is the most anterior of the places of production of the three voiceless stop-plosives in the English language, so that the

measurement of oral pressure can be done with the least degree of insertion of a sensing probe, with the least complex insertion pathway for a sensing probe, with the least likelihood of recording artifact from the blockage of the sensing probe by saliva, and with the least likelihood of recording artifact from articulatory interference with the sensing probe; (4) the compression compliance between the airway-occluding structures (that is, the two lips) at the place of production for /p/ is greater than that for the other voiceless stop-plosives in the English language, so that on peroral insertion of a sensing probe there is the greatest likelihood of an airtight seal being formed around the sensing probe during consonant closed-phases and probably the least encumbrance to the normal articulatory process; and (5) the adequacy of closure of the oral segment, a necessity in application of the method, is more easily determined at the lips on /p/-element production than on other voiceless stop-plosives in patients with structural or neuromuscular disorders on whom it is desired to use the method.

The voiced vowel /i/ was chosen for inclusion in the utterance sample from among the many vowel possibilities in the English language. The /i/, a high, front, unrounded vowel, offered the following merits for its selection from the list of candidates: (1) it has been shown empirically

that velopharyngeal closure is airtight during /i/ and other high vowels produced in non-nasal phonetic contexts (Thompson and Hixon, 1979) so that /i/ meets one of the important central constraints imposed by the theoretical basis underlying the method; (2) the front place of production of /i/ in combination with /p/, places the focus of articulatory activity for the utterance sample in a single region (anterior) of the upper airway, so that the performance task is simplified for normal subjects and for those patients who are neuromuscularly impaired and may have greater difficulty in performing a more demanding set of articulatory gestures; (3) the production of /i/ does not involve lip-rounding, or extensive excursions of either the tongue or the mandible, so that flow artifacts (even though miniscule) related to articulatory motions are minimized; and (4) the production of /i/ does not involve extensive articulatory motions in the vicinity of the anterior oral segment, so that there is little likelihood of an air leak around the border of the oronasal mask used to trap flow (see Equipment) as a result of subject-mask interfacing problems.

Finally, considerations of a supra-segmental nature were also taken into account in the design of the present utterance sample. An attempt was made through instruction to the subject to influence the form of the breath group used. That is, by telling the subject to take a breath of

twice normal depth before utterance and to produce utterance on a single, continuous expiration, it was reasoned that breath group conditions would be similar to those typical of conversational speech. During such speech, subjects make pre-utterance inspirations to about 60% of the vital capacity and then produce utterances on uninterrupted expirations that extend through the mid-range of the vital capacity (Hixon, Goldman, and Mead, 1973). Having the subjects perform the utterance sample at normal loudness, normal pitch, and normal quality was intended to provide for utterance conditions that were routinely natural to the subjects and closely approximated their "normal" manner of using the larynx during vowel production. The choice of the syllable as the fundamental utterance unit within the sample was prompted by this unit's simplicity from the viewpoint of subject performance, and the ease with which it could be controlled for linguistic stress and rate of utterance. With regard to linguistic stress, it was desired that it be the same on each syllable to maximize the consistency of the drive provided to the larynx and upper airway by the respiratory apparatus (that is, to maintain a steady tracheal pressure contour), and to maximize the consistency of the laryngeal adjustment associated with successive vowel elements in the syllable train. With regard to rate of utterance, it was deemed important to

control it to maximize the consistency of the laryngeal adjustment associated with successive vowel elements and to provide vowel productions of sufficient duration to have the larynx assume at least quasi-static resistance values during their mid-points. Selection of the specific repetition rate of 1.5 syllables per second was influenced by a compromise between the issues just mentioned and the need to insure that velopharyngeal closure would be maintained airtight during the utterance sample. It has been demonstrated empirically that utterance rates below this value are often accompanied by intermittent velopharyngeal openings (Thompson and Hixon, 1979), which would be unacceptable were it desired to make measurements with the present method.

Equipment

Two aspects of subject performance were recorded: oral air pressure (hereinafter referred to as pressure) and airway-opening flow (hereinafter referred to as flow).

Pressure was tapped and transmitted via a small polyethelene catheter (1.5 mm bore, 20.0 cm length) whose proximal end was positioned in the oral cavity (see Procedure) and whose distal end was coupled to a differential air-pressure transducer. The output signal of the transducer was led to a carrier amplifier where it was amplified and low-pass filtered such that components above

30 Hz were attenuated markedly. The resulting pressure-analog was displayed on one channel of a two-channel storage oscilloscope for monitoring, and on one channel of a two-channel thermal recorder for permanent recording.¹ The latter was operated at a paper speed of 20 mm/sec. System calibration was performed against a U-tube water manometer arranged in parallel with the polyethelene catheter.

Flow was channeled through a large, hard-rubber, anesthesia mask positioned over the mouth and nose. Flow from the mask was sensed by a double-coned, one-square inch, Silverman-type pneumotachometer coupled to a second differential air-pressure transducer matched to the one used to sense oral pressure.² The output signal of this transducer

1. During pilot study, a three-channel thermal recorder was used so that speech audio could be recorded simultaneously with pressure and flow. Recording was accomplished with a three-component equipment set up: (1) a contact throat-microphone; (2) a DC amplifier; and (3) one channel of the thermal recorder. It was intended that speech audio be used as an aid to the temporal segmentation of phonetic events. Use of this recording was abandoned because points of measurement interest in the pressure and flow recordings proved to be validly and reliably identifiable from the pressure and flow data alone.

2. Resistance offered by the flow-channeling and -sensing equipment was measured to be less than 0.5 cm H₂O/LPS over the range of flows observed in the present study. This value is negligible in comparison to the resistances measured for subject utterances and so equipment resistance has been neglected in subsequent considerations.

was conditioned (amplified and filtered) through a second carrier amplifier in the same manner as just discussed for pressure. The resulting flow-analog was monitored and recorded permanently on the remaining channels of the storage oscilloscope and the thermal recorder, respectively. System calibration was performed through the use of a continuously-variable, vane air-pump whose output was directed through an air rotameter arranged in series with the pneumotachometer.

An electronic metronome was used to aid subjects in the pacing of their utterances. This metronome was operated at a rate of 1.5 beats/sec and provided a synchronous light-flash and audible click to guide the subjects.

Procedure

Each subject was seated upright and positioned so that the monitoring and recording systems were out of his visual field. Next, the anesthesia mask was placed over the subject's mouth and nose so as to form a comfortable and airtight seal between it and the subject's face. The pressure-sensing catheter then was threaded through a small opening in the side of the mask, and its proximal end was positioned in the midline of the oral cavity approximately 1.0 cm behind the central incisors. Following this, the subject was informed of the nature of the task to be performed and was instructed to model his performances after

those generated by an investigator. Utterances made by each subject had to meet the criteria discussed previously under the section on Utterance Sample. Subject utterances judged to be inappropriate copies of the model provided by the investigator were not accepted, and additional samples were elicited until appropriate copies were obtained. Repeated requests for utterance samples were made of the subject until three acceptable syllable-trains were obtained. Those subject performances which met the utterance criteria were culled from the permanent thermal recordings for analysis.

Record Analysis

Figure 1 is an example of the pressure-flow records obtained through use of the present method. Oral pressure and airway-opening flow are shown in the upper and lower parts of the figure, respectively.

The seven maxima observed in the upper part of the figure correspond to the peak oral pressure obtained during the closed phases of the seven /p/-segments of the utterance sample. These peaks are seen to be relatively consistent and to be hovering in the neighborhood of 7.0 cm H₂O. Increase in pressure to each maximum is very rapid and presumably has its beginning closely time-locked to closure of the oral airway at the lips. Decrease in pressure from each maximum is also very rapid and presumably has its

Figure 1. Example of the pressure-flow records obtained.
 P_o = oral pressure and $\dot{V}_{ao}$ = airway-opening flow.

beginning time-locked to release of oral airway closure. The seven pressure minima seen to immediately follow the /p/-segments in Figure 1 correspond to the pressures associated with the seven /i/-segments of the utterance sample. These minima are seen to be in the form of prolonged pressure plateaus that are highly consistent and of a magnitude of less than 0.1 cm H₂O.

The seven plateau-like portions of the record in the lower part of Figure 1 correspond to the flows obtained during the same seven /i/-segments just mentioned. These flows are seen to be relatively consistent and of an approximate magnitude of 0.19 LPS on the average. Flow minima between the vowel segments represented in Figure 1 are at zero and presumably coincide with closures of the oral airway. The extremely rapid increases in flow following these zero flows presumably are associated with the opening of the oral airway upon plosive release subsequent to the attainment of peak oral pressure. The flow maxima associated with these releases are greater than those shown in those instances when the tracing reaches recording pen limitation beyond full-scale deflection.

Records were subjected to analysis along the following lines. First, to preclude possible utterance performance end-effects, the first two and last two vowel segments in each syllable train were disregarded and only the middle

three vowels in the train were considered. Next, an estimate of tracheal pressure at the approximate mid-point of each vowel studied was determined as follows. The peak oral pressures on the third, fourth, fifth and sixth productions of /p/ were identified on the records and interconnected with those for their adjacent mates by straight lines. The assumption was made that the contour formed as a result of a linear interpolation between the four oral pressure peaks was the best available estimate of the prevailing tracheal pressure contour associated with the middle portion of the syllable train. Next, the time points midway between the designated adjacent pressure peaks on the records were identified and the corresponding interpolated pressures were noted. Thus, a separate estimate of tracheal pressure was provided for each of the three vowels under analysis. In Figure 1, points of measurement for the three vowels of interest are indicated by the arrows numbered 1, 2, and 3 at the top of the figure. Pressures were expressed in cm H₂O.

An estimate of pharyngeal pressure at the approximate midpoint of each vowel studied was determined by noting the magnitude of the oral pressure coincident with the moment of tracheal pressure measurement just discussed. Thus, a separate estimate of pharyngeal pressure was provided for each of the three vowels of interest. Pressures were expressed in cm H₂O.

An estimate of translaryngeal flow at the approximate midpoint of each vowel studied was determined by noting the magnitude of airway-opening flow coincident with the moment of tracheal-pressure and pharyngeal-pressure measurements just considered. Thus, a separate estimate of translaryngeal flow was provided for each of the three vowels studied. Flows were expressed in LPS.

Laryngeal airway resistance was calculated for each vowel studied as follows: translaryngeal pressure was determined as the difference between the measured tracheal and pharyngeal pressures; this difference was then divided by the measured translaryngeal flow. Calculation yielded a separate resistance value, expressed in $\text{cm H}_2\text{O/LPS}$, for each of the three vowels studied in each of the three syllable trains analyzed for each subject. (In Figure 1, the three resistance values are 37.4, 37.9, and 36.8 $\text{cm H}_2\text{O/LPS}$ for vowels 1, 2, and 3, respectively.) The mean resistance was determined for each syllable train (for the three vowels in Figure 1, this value is 37.4 $\text{cm H}_2\text{O/LPS}$), and the grand mean, the mean of the three means, was then determined as the criterion score for each subject on the utterance task.

RESULTS

Reliability of Criterion Scores

The reliability of the criterion scores for the utterance sample was determined through the use of intra-class correlation technique. The obtained reliability coefficient associated with data derived from the mean of three performances of the utterance sample by the subjects was .96. A coefficient of this magnitude indicates that the mean of three determinations is a highly reliable estimate of the true value for the resistance measures of interest in this study.

Criterion Scores

Table 1 presents the criterion scores obtained for the 15 subjects studied. Subjects are listed down the table in order of increasing chronological age. The resistance values for the subject group yield a mean of 35.7 cm H₂O/LPS, with a range of 30.0 cm H₂O/LPS to 43.1 cm H₂O/LPS, and a standard deviation of 3.3 cm H₂O/LPS. Inspection of the data in Table 1 suggests that no relationship exists between chronological age and the magnitude of laryngeal airway resistance during vowel production. This

Table 1. Subject identifications, ages, and criterion scores.

Subject (Initials)	Age (Years-Months)	Resistance (cm H ₂ O/LPS)
DM	21-10	30.0
JB	23-8	35.5
KG	24-2	41.7
DB	24-8	35.8
JT	24-11	36.1
DS	27-0	43.1
JL	28-8	34.6
JK	31-8	32.3
JM	32-4	34.4
RC	32-5	36.0
RW	34-4	32.1
TG	38-5	33.0
KW	38-8	37.3
TH	40-0	36.8
DW	40-6	37.4
		Mean 35.7
		Range 30.0-43.1
		SD 3.3

impression is corroborated statistically through the computation of a Spearman rank-order coefficient of .16 between the two data sets.

DISCUSSION

Adequacy of the Method

The data of the present thesis are interpreted as strongly supportive of the reliability and validity of the proposed clinical method for estimating laryngeal airway resistance during vowel production. An estimate of reliability, as statistically evaluated through intraclass correlation technique, resulted in a highly satisfactory coefficient based on the mean of three sets of measurements on three repetitions of the utterance sample. Validity is inferred from the magnitude of the airway resistances calculated, the low inter-subject variability on the resistance values, the extent to which the data agree with the theoretical basis for the method itself, and the very close agreement -- discussed next -- between data obtained on the subjects studied here and subjects studied in earlier reports where invasive experimental procedures were used to determine resistance.

Recall that the average laryngeal airway resistance calculated for the 15 adult males of the present study was 35.7 cm H₂O/LPS. Several investigations include mean data that allow for a reasonable comparison to the present data

in terms of subject and utterance-sample comparability. The three most extensive of such reports include the works of Kunze (1962), Sant and Logemann (1970), and Shipp and McGlone (1971). Each of these investigators used puncture of the trachea with a hypodermic needle to obtain records of tracheal pressure. Each also used an oronasal anesthesia mask to trap airway-opening flow. In Kunze's investigation, flow was derived from the recordings of a respirometer coupled to the mask, while in the Sant and Logemann and the Shipp and McGlone investigations flow was determined through use of a pneumotachometer coupled to the mask. Each of the three reports was based on the study of a sizeable group of adult male subjects producing sustained vowels. For comparison with the present findings, the following data have been considered: from Kunze (1962) -- the data for 10 subjects producing the vowels /ae, a, o, u, i/ at 50% of their vocal intensity ranges and at 30% of their vocal fundamental frequency ranges; from Sant and Logemann (1970 -- the data for 18 subjects producing the vowel /ɔ/ at the "medium" point of their vocal sound pressure level ranges and at 25% of their vocal fundamental frequency ranges; and, from Shipp and McGlone (1971) -- the data for 14 subjects producing the vowel /a/ at a presumed average 50% of their vocal sound pressure level ranges

(data collapsed from the 25% and 75% levels) and at 30% of their vocal fundamental frequency ranges.

The bar graph in Figure 2 summarizes data from the present study and data from the three investigations mentioned. The data shown for comparison investigations are mean laryngeal airway resistances (expressed in $\text{cm H}_2\text{O/LPS}$) calculated by the present author from the data provided in the various reports. It is readily observable from Figure 2 that the mean resistance obtained with the present clinical method is remarkably similar to the mean resistances obtained in the earlier invasive investigations. In fact, when the mean data from the present study are compared to the weighted mean data from the earlier three investigations indicated in Figure 2, the two sets of data (the present for 15 subjects and the earlier for 42 subjects) differ by a mere 1.5 $\text{cm H}_2\text{O/LPS}$. The closeness in value of the present data to those provided by invasive procedures bears forcefully on the face validity of the present method and suggests strongly that the present method is fully adequate as a means for estimating laryngeal airway resistance during vowel production.

The Method as a Routine Clinical Tool

The results of the present thesis are very encouraging with regard to the potential usefulness of the present method as a routine clinical tool for estimating

Figure 2. Graphic representation of the mean laryngeal airway resistances obtained in the present and earlier investigations.

laryngeal airway resistance during vowel production. An important aspect of the resistance data reported is the low intersubject variability (that is, the small standard deviation). Pending further needed research (see next section) on large groups of normal subjects and on subjects with demonstrated laryngeal airway resistance control problems during voicing, this low intersubject variability suggests strongly that it should be possible to use the present method to obtain data that will discriminate between individuals with normal laryngeal function and those with disordered laryngeal function.

A second important aspect of the resistance data reported in this thesis is that a highly stable criterion score (that is, a high intrasubject reliability) results from analyses made on only three performances of the utterance sample specified in the protocol. This means that the present method is clinically practical with regard to the time required to collect the needed pressure-flow data, to analyze the records, and to calculate the airway resistance offered by the larynx. More specifically, once the examiner is intimately familiar with the method proposed, the total time required to obtain a criterion score is typically only five minutes. Beyond the present thesis, it would seem a relatively simple task to computerize the present method such that the required pressure-flow values could be machine read and the resistance calculations done

automatically. This modification of the method would render its running time to essentially that taken to collect the data for three acceptable utterance samples from the subject.

In addition to the minimal time-requirement involved in use of the present method, there are other attractive aspects of the method from the viewpoints of both the subject and the examiner. The utterance task required of the subject is simple and easy to perform, involving only the repetition of a single syllable over and over in the same fashion. Although the present study was restricted to adult male subjects, it seems reasonable to assume that even young children and many difficult-to-test individuals would be capable of performing the utterance task called for in the method. The present method causes no discomfort to the subject during data collection and it must be considered essentially noninvasive. Furthermore, encumbrance to the normal speech-production process from use of the method appears to be essentially nil and at no time is the subject placed at physical risk.

Important practical aspects from the examiner's point of view include the fact that a physician is not required for protective supervision during data collection. In addition, there are no special ethical considerations to be dealt with beyond those routinely associated with the practice of speech-language pathology. Examiners with very limited experience in the use of clinical equipment can be trained

easily and quickly in use of the present method. And, fortunately, the method, as it has been described, capitalizes on measurement technology that is currently available in many speech-language pathology clinical settings, particularly those found in hospital environments. With regard to the specific equipment used, that required by the method is of only moderate expense and when appropriately configured is reasonably portable. A wide variety of laryngeally-based clinical disorders can be studied with the present method (see next section) and the same basic equipment required in the method can be used to both evaluate and manage disorders manifested in the resistance parameter. Not only does the method provide precise data on laryngeal airway resistance, it also provides permanent records of the aeromechanical behavior of the larynx that can be used to track the status of the resistance parameter. Such data can be used to document and chart changes in function, to make numerical comparisons between subject performances and baseline norms, to compare values among disordered populations, to compare values from clinic to clinic, and to quantify the success of various mechanical management programs (for example, teflon injection of a paralyzed vocal fold). Data provided by the present method also complement data obtained by other methods of observation with which most

clinicians are already familiar. In summary, as a clinical tool, the present method would appear to be extremely powerful, useful, and welcomed.

It is relevant to close this section of the discussion by considering examples of the use to which the method has been put subsequent to its standardization in this thesis. At the time of this writing, the method has been used clinically with six different individuals exhibiting voice dysfunction. Two of these individuals, one presenting resistance values above and one presenting resistance values below the presumed normal laryngeal airway resistance continuum, have been chosen for consideration here.

BT, a healthy 21 year-old female university student, was referred for functional dysphonia. She exhibited a low-pitched, harsh, breathy voice, the quality of which had become unacceptable to her. Indirect laryngoscopic examination revealed bilateral vocal fold nodules. Information in her case history suggested vocal abuse as the probable cause of her nodules and, in turn, her presenting dysphonia. An inordinately heavy vocal schedule as a drama student, an active social-life in noisy environments, and continuing nightly performances as a singer in stage musicals, were judged to be the principle aggravating factors associated with her dysphonia. As a part of the evaluation of BT's laryngeal function during voice production, the present method was used to determine her laryngeal airway resistance on vowels. Resistance was calculated to be 22.9 cm H₂O/LPS. This value is 35.9% lower than the average value obtained for the subject group studied in the present thesis and 23.7% lower than the value obtained for the subject with the

lowest resistance in the same group.³ It seemed reasonable to assume that BT's markedly low laryngeal airway resistance was related to the presence of her bilateral vocal fold nodules and the likelihood that they were precluding her from attaining a firm approximation of the vocal folds along their entire length. An intensive voice-therapy program was used with BT. This program was conventional with regard to the identification and elimination of her abusive laryngeal behaviors and with regard to the use of symptomatic voice modification procedures to raise her vocal pitch and reduce her harshness and breathiness. Coupled with these standard procedures, BT was given training in the use of the present method as a biofeedback means of obtaining information concerning her laryngeal airway resistance during vowel production. This information was provided on the thermal recorder display discussed earlier in this thesis under the section on Equipment. Approximately three months following the initial airway resistance evaluation, with its result of 22.9 cm H₂O/LPS, BT was dismissed from therapy and placed on a self-monitoring vocal-hygiene program. Determination of laryngeal airway resistance immediately before dismissal revealed a value of 34.3 cm H₂O/LPS, a resistance of approximately the average magnitude as that found for the subject group studied in the present thesis and an increase for BT of 33.2% in the magnitude of her airway resistance from the time of her initial evaluation.

3. It should be noted that the subject group used for this comparison included only adult males. In lieu of needed normative data on adult female subjects, it has been assumed that this comparison is appropriate for two reasons: first, BT demonstrated typical adult-male resistance values once her voice had returned to a quality adequate for release from therapy, and second, preliminary findings on a small number of adult females show them to fall within the range of values determined for the adult males studied here.

BT's case is significant to the present thesis for at least two reasons. She represents the first individual on whom laryngeal airway resistance changes have been documented in response to a management program and the first individual to use laryngeal airway resistance in a biofeedback mode as a part of a program of rehabilitation. It seems clear from even this one case example, that the present method can play an important role in the evaluation and management of dysphonias that have functional bases.

LD, a 57 year-old male who had suffered multiple, bilateral, cerebral-vascular accidents two years before, was referred for evaluation of his speech production capabilities. Study revealed that LD had a mixed dysarthria whose perceptual correlates included hypernasality, articulatory imprecision, short phrases, and a marked strained-strangled voice quality. The latter was judged to be the most prominent deviant characteristic of his speech behavior. Included within a battery of physiological examinations for motor-speech integrity, was the present method for estimating laryngeal airway resistance. Application of the method revealed a laryngeal airway resistance of 66.0 cm H₂O/LPS for vowel utterances. This value is 85% higher than the average resistance determined for adult males studied in this thesis and 53% higher than that obtained for the subject with the highest calculated resistance. The extremely high resistance determined for LD was consistent with his prominent strained-strangled voice quality and was assumed to be related to a probable spastic component of his laryngeal control problem. Noticeable improvement in LD's voice quality was achieved when he raised his modal fundamental frequency level, rotated his head backward, or initiated his utterance from a higher lung volume. Determination of laryngeal airway resistance under these three conditions revealed values that were lower than usual for LD, the most marked improvement being a decrease in resistance to 52.0 cm H₂O/LPS when utterance was initiated from a high lung volume. It was assumed that this

improvement was related to passive abduction of the vocal folds brought about by the tracheal tug associated with a lower diaphragm position at high lung volumes. In LD's case, it was recommended that he be started on a voice modification program that was behavioral, and that the present method be used as a means of revealing those conditions which optimally reduce his laryngeal airway resistance during voicing.

LD's case illustrates the value of the present method in the detailed evaluation of individuals with laryngeally-based dysarthrias and the extent to which the specification of laryngeal airway resistance can be used to aid in determining fruitful avenues of management.

Future Considerations

The present thesis was methodological and exploratory. Study of laryngeal airway resistance for 15 adult males was intended to determine the face validity of the present method and to present a small initial pool of data for the benefit of further research considerations. Additional laryngeal airway resistance data are needed to further establish the efficacy of the present method as a routine clinical tool for the quantification of laryngeal function.

Specifically, the need remains to determine the range and central tendencies of laryngeal airway resistance values exhibited by the full variety of normal subjects. Such study necessitates the collection of normative information on large groups of males and females encompassing all

age ranges. With the collection of normative data on laryngeal airway resistance, it is hoped to be eventually possible to effectively differentiate between those individuals with normal and disordered laryngeal function as pertains to resistance control. To these ends, various types of voice disorders warrant systematic study with the present method in hopes of discovering how the resistance parameter is influenced by disordered production of voice and in evaluating changes with management. Some of the more obvious areas of study in this regard include so-called hyperfunctional and hypofunctional voice disorders without organic bases, neurologically-based voice disorders, and voice control problems associated with such disorders as profound hearing impairment. The ultimate hope would be the possible establishment of approximate cut-off points for the range of laryngeal airway resistance values during vowel production, below and above which dysfunction in control of laryngeal airway resistance could be assumed. In this regard, it may even eventually be possible clinically to more efficiently designate those individuals with borderline resistance control skills.

Another group of studies that could be done using the present method involves observations of changes in laryngeal airway resistance under a wide variety of conditions of voicing. For example, the present method provides

a useful and simple tool for the study of factors believed to influence laryngeal airway resistance, such as vocal sound pressure level, vocal fundamental frequency, voice quality, and whispering. Thus, studies of normal control mechanisms are seemingly more readily achievable for the researcher than has been the case in the past with invasive procedures.

Those wishing to use the present method routinely in a clinical setting might well consider several factors that expand the applicability of the method. First, the oro-nasal anesthesia mask used in the present study provides an adequate fit to the subjects chosen for study here but not to all subjects. Those wishing to use the method on women, children, or individuals with various oro-facial disorders would be well advised to obtain a series of masks similar to the one used in the present study, but of different sizes.

A second consideration to extend the general applicability of the method pertains to rendering the technique useful in those persons with valving incompetence at either the velopharynx or the lips. Recall from the section on CONCEPTUAL DEVELOPMENT that airtight seals need to be made at these two sites coincident with laryngeal opening to enable a moment of pressure equilibration for accurate tracheal pressure estimation. Failure to meet this requirement leads to a tracheal pressure estimate that

is lower than the actual tracheal pressure so that the resistance value calculated will be lower than the actual resistance. In the case of either the velopharynx or the lips, valving incompetence is manifested in the recording obtained with the present method by flow not returning to zero during the closed phase of the stop consonant production. This problem is easily solved in the case of the velopharynx by placing a nose clip on the subject before placing the mask over his/her mouth and nose. This modification results in an infinite resistance along the nasal pathway so that flow escape through the incompetent velopharyngeal valve is precluded. In the case example of LD, discussed in the previous section, data were obtained in this fashion to counteract a velopharyngeal leak that was a contributing factor to his speech disorder. In the case of valving incompetence of the lips around the pressure-sensing tube, one should consider the option of selecting a stop-plosive consonant with a more posterior placement in the oral airway and the positioning of the pressure-sensing tube via other routes. Placement at the midline of the oropharyngeal cavity by way of pernasal insertion or by way of insertion along the buccogingival sulcus are two alternatives (Warren and DuBois, 1964; Arkebauer, Hixon and Hardy, 1967). While these two are far more invasive and difficult to use than simply positioning the pressure-sensing tube behind the lips for /p/, they

nonetheless provide the data that are required to make useful laryngeal airway resistance calculations.

A third area of consideration for extending the applicability of the method clinically involves a compromise to the actual method proposed here, but one that seems acceptable under certain circumstances where a reasonably close approximation to the true resistance value is better than none. Clinical experience with the use of the method has shown that in a very small number of individuals the simultaneous measurement of oral pressure and airway-opening flow is difficult to achieve. This is occasionally the case with a very young subject or with a subject who shows a substantial degree of neuromuscular involvement in the orofacial region. As an alternative to abandoning the relevant data that can be provided on such subjects, it has been found useful to record oral pressure and airway-opening flow during separate repetitions of the utterance sample. Recordings of the two variables are then measured from the separate records and combined to determine an approximate value for laryngeal airway resistance. Under these circumstances, it seems advisable to average a greater number of resistance measures on a greater number of syllable repetitions in an attempt to more accurately estimate the subject's mean laryngeal airway resistance.

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