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Indirect estimation of laryngeal resistance via airflow redirection

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Abstract

Objectives—To indirectly estimate aerodynamic parameters of laryngeal resistance (R_L) and aerodynamic power from a subglottal pressure (P_s) data trace obtained using the airflow redirection system.

Methods—During airflow interruption, the airflow redirection tank fills capacitively with pressure until reaching the subject's P_s . Therefore, the time constant, τ , can be extracted from the data trace and used to calculate R_L . The validity of applying this method to the estimation of R_L was demonstrated using a computer model. Estimations were made for values of 10, 20, 30, 40, and 50 cmH₂O/l/s. Twenty subjects performed ten trials on the experimental system designed to measure P_s . Values of R_L and aerodynamic power were then calculated.

Results—The computer model simulation yielded a maximum measurement error of 3.00 % and a mean error of 1.78 %. In human subject testing, mean laryngeal resistance was 22.61 ± 8.65 cmH₂O/l/s, mean P_s was 6.91 ± 1.94 cmH₂O, and mean aerodynamic power was 0.247 ± 0.170 kPa * l/s.

Conclusions—The proposed method of data analysis enables a clinician to estimate R_L and aerodynamic power from a single experimental trial designed to measure P_s . This provides the clinician with an aerodynamic function report which can be used to analyze patient health and treatment efficacy.

Keywords

Laryngeal resistance; airflow redirection; subglottal pressure; aerodynamic power

INTRODUCTION

Aerodynamic parameters of phonation such as subglottal pressure (P_s) and airflow have been demonstrated to reflect laryngeal health (1,2). P_s can be measured during sustained phonation and also at the phonation threshold, at which point it is termed the phonation threshold pressure (PTP) (3). Measuring P_s at the phonation threshold can provide insight on the effort required for a patient to initiate phonation. Airflow is often described using mean flow rate (MFR), which provides an estimate of glottal impedance and integrity (4). Glottal resistance (R_g), a third basic aerodynamic parameter, is defined as the pressure across the glottis divided by the flow through the glottis (5). Laryngeal resistance (R_L) is a similar parameter and is defined as P_s divided by translaryngeal airflow (6). The three parameters of pressure, flow, and resistance are related according to this equation, an analog of Ohm's Law.

Measurements of R_g or R_L can provide information concerning the physical characteristics of the airway, as well as the mechanical properties of the laryngeal tissues. Netsell *et al.* found that females typically have a higher R_g than males. Because resistance is dependent upon the size of the airway, this could be attributed to females having a smaller larynx (7). Several other factors contribute to R_g , including degree of vocal fold adduction, roundness at glottal entry and exit (8), and the speed of the air particles across the glottis (9). Various methods have been proposed to measure R_L , including that proposed by Smitheran and Hixon (6). This method interpolates translaryngeal pressure and airflow during the repetition of plosive consonants followed by voiced vowel sounds. While this method recorded values of R_L similar to those measured using invasive methods, it can require intensive subject training (10).

To avoid potential variance associated with subject-controlled labial interruption, mechanical interruption utilizing rapidly firing balloon valves was introduced. Bard *et al.* demonstrated that pressure measured in the oral cavity during valve closure correlated well with pressure measured directly in the trachea (11). Jiang *et al.* employed a similar method which was also validated using a simultaneous direct measurement (12). Though mechanical interruption eliminated variability caused by subject-controlled interruption, it introduced a new source of variability in the form of laryngeal reflexes. Kearney *et al.* used air puff stimuli to elicit the laryngeal adductor reflex (LAR) (13) and found the minimum latency to be 68 ms. Average latencies were between 150 to 175 ms. Eliciting reflexes during airflow interruption can lead to inaccurate estimation of P_s , and subsequent inaccurate calculation of R_L , as vocal fold closure caused by the LAR results in elevated levels of P_s (14).

Several modifications to the airflow interruption system have been proposed to eliminate the effect of laryngeal reflexes while still maintaining the consistency of mechanical interruption. Two methods, measuring P_s consistently at 150 ms after the interruption (15) and applying auditory feedback during subject testing (16), were proposed by Hoffman *et al.* Measuring P_s using a reliable time from interruption onset decreased intrasubject variability by eliminating the subjectivity of intraoral pressure plateau analysis. The addition of auditory feedback to the airflow interruption system also decreased intrasubject variability, producing more consistent intraoral pressure traces which led to less subjective analysis. A third technique was introduced by Baggott *et al.* and modified the airflow interruption system by attaching a five liter tank into which subject airflow could be redirected (17). Subject P_s could be measured in this tank, as opposed to within the small volume of the airflow interrupter. Three 135 ms interruptions were used instead of one 500 ms interruption to avoid the elicitation of reflexes. The airflow redirection method was validated using both a laryngeal model and a simultaneous direct measurement through a tracheotomy tube connected to a pressure transducer.

While airflow redirection has previously only been used to estimate P_s , we propose that it can also be used to estimate R_L without changing the data collection process. Data are analyzed to determine the time constant, τ , at which pressure inside the attached tank is equal to 63.2% of the subject's P_s . The time constant and R_L are directly correlated by the constant capacitance of the tank.

THEORY

During phonation, the larynx can be modeled as an electrical circuit (18), with predictable relationships occurring among subglottal pressure, airflow, and resistance. The airflow redirection tank used in this experiment acts as a capacitor during balloon valve interruption (figure 1). After the onset of the interruption, it immediately begins building charge, or pressure. The time constant, τ , can be found using an ideal gas model of capacitance in a closed volume. As velopharyngeal leaking could alter the volume, precautions were taken to ensure it did not occur. A nose clip was worn to prevent airflow through the nasal cavity and the mouthpiece

was held firmly in the mouth against the labial surface of the teeth to prevent leakage through the mouth.

Before applying the equation relating laryngeal resistance, capacitance, and the experimentally determined τ , it is necessary to solve for the unknown value of capacitance using the ideal gas law. P is pressure, V is the volume of the tank, V_1 is the mean gas volume (using the atmospheric conditions of Madison, WI), R is the gas constant, T is the temperature in Kelvin, V_{mol} is the volume of one mole of gas, n is the number of moles of gas, and C is capacitance:

$$PV=nRT \quad (1)$$

$$P=\left(\frac{n}{V_{mol}}\right)RT=\frac{RT}{V_1}, \quad (2)$$

since

$$V_1=\frac{V_{mol}}{n} \quad (3)$$

$$C(\Delta P)=V \quad (4)$$

$$C\left(\frac{RT}{V_1}\right)=V \quad (5)$$

Since $R=84,784 \frac{\text{cmH}_2\text{O} \cdot \text{ml}}{\text{mol} \cdot \text{K}}$ (19), And using a barometric pressure of 29 inHg (20), which equals 1001.4 cmH₂O,

$$V_1=25,240 \text{ ml/mol}$$

The volume of the tank is 5000 ml (17). Therefore,

$$C=\frac{VV_1}{RT}=\frac{(5,000\text{ml})(25,240\frac{\text{ml}}{\text{mol}})}{(84,784\frac{\text{cmH}_2\text{O}\cdot\text{ml}}{\text{mol}\cdot\text{K}})(298\text{K})}=4.995 \text{ ml / cmH}_2\text{O} \quad (6)$$

This value for C can then be used in the following equation:

$$\tau=R_L \times C \quad (7)$$

τ is the time required during an interruption to increase in pressure from $P(n)$ to $P(n+1)$ in the following equation, where n is an integer representing t/τ :

$$P(n) = P_s (1 - e^{-n}) \quad (8)$$

For example, when $n = 1$, τ is the time required for pressure to increase from 63.21% to 86.46% of P_s . When $n = 2$, τ is the time required for pressure to increase from 86.46% to 95.02% of P_s . The time constant can be determined experimentally from tank pressure data traces. Once τ is found, the equation can be rearranged to isolate laryngeal resistance as the unknown variable:

$$R_L = \frac{\tau}{C} \quad (9)$$

If P_s is known and R_L can be extracted from the P_s data trace, aerodynamic power can also be calculated by manipulating two equations:

$$P_s = I \times R_L \quad (10)$$

where I is airflow. Aerodynamic power is usually found using the equation:

$$P_A = I \times P_s \quad (11)$$

where P_A is aerodynamic power. If I is unknown, it can be found in terms of P_s and R_L by manipulating equation 9.

$$I = \frac{P_s}{R_L} \quad (12)$$

Substituting I in equation 10 for its equivalent shown in equation 11, the formula for aerodynamic power becomes:

$$P_A = \frac{P_s^2}{R_L} \quad (13)$$

Therefore, the aerodynamic parameters of laryngeal resistance, aerodynamic power, and airflow can all be obtained from one subglottal pressure data trace.

MATERIALS AND METHODS

Experimental Design

The testing apparatus is identical to that described in Baggott et al. (17) (figure 2). Subjects phonate a sustained /a/ into a mouthpiece (Series 9063; Hans Rudolph) and are interrupted for approximately 135 ms by a rapidly inflating balloon valve (Series 9340 2-way Shutoff Valve, Inflatable-Balloon Type; Hans Rudolph). Three interruptions occur per trial, during which pressure is redirected into an attached five liter air tank that is pre-pressurized to 3.5 cmH₂O to facilitate the pressure rise occurring during the interruption. The tank is constructed from 10.16 cm diameter PVC pipe that is covered at both ends and houses three ports. The first port is connected to a constant pressure source (QB2TFEE002 pressure regulator valve, RG4514 volume booster, DSY002 pressure sensor, Proportion Air, McCordsville, IN). The backflow

of air from the tank to the pressure source is prevented by a custom low-flow one-way valve (Series 1810; Hans Rudolph, Kansas City, MO). This port also serves as the point of connection for a Magnehelic pressure gauge (R990108M1621; Dwyer Instruments, Michigan City, IN) and a Pneumotach Amplifier (Series 1110; Hans Rudolph) which served as the pressure transducer. The Pneumotach Amplifier outputs a voltage to the Data Acquisition System via a Baby-N Connector Block (BNC-2110; National Instruments, Austin, TX), a DAQ PCMCIA card (PCI-6036E, National Instruments), and custom-programmed LabVIEW 8.0 software (National Instruments). The second port is used for pressure release. The third houses the mouthpiece and inflatable balloon valve, which are connected to each other and the tank via 1.905 cm diameter PVC tubing and a second low-flow one-way valve. Balloon valve inflation is controlled by a custom balloon control box and is initiated by a signal from the custom-programmed LabVIEW software. A Digital Sound Level Meter (33—2055; Radioshack, Fort Worth, TX) connected to the data acquisition system is used to monitor the acoustic signal throughout the trial.

Human subject testing

Subject testing was done under the approval of the Institutional Review Board of the University of Wisconsin-Madison. Twenty subjects responding to flyers placed around the University of Wisconsin-Madison participated and were compensated with \$20. No requirements were made concerning demographics or health, as the experimental device is designed to work on all subjects. Subjects performed ten trials. A trial consisted of phonating a constant /a/ into the mouthpiece at 72 dB ($\pm 2\%$) for approximately five seconds, during which three balloon valve interruptions occurred, each 135 ms in length. A computer program provided continuous feedback to the subject concerning amplitude and frequency to facilitate constant, consistent phonation. Subjects wore a nose clip (Series 9105; Hans Rudolph) to prevent the flow of air through the nasal cavity.

Data analysis

Mean and standard deviation values for laryngeal resistance, subglottal pressure, and aerodynamic power were determined. Values of laryngeal resistance and aerodynamic power were calculated using equations 9 and 13 discussed in the theory section.

To analyze the data, a semi-automated analysis method was employed. Before analysis, the data were low-pass filtered at 100 Hz to eliminate excess noise. Subglottal pressure was measured by finding the maximum voltage of the trial, and then multiplying by the calibration constant ($10 \text{ cmH}_2\text{O} / 1 \text{ V}$). The voltage of each of the first three time constants was measured by multiplying the subglottal pressure voltage and .6321, .8646, and .9502, respectively. Then, a search was conducted in the data for the time at which the voltage of each time constant occurred. The laryngeal resistance was calculated by summing the interruption time between time constants and dividing by the previously determined capacitance of the airflow redirection tank.

Each trial consists of three balloon valve interruptions. The tank only fills when the balloon is inflated; therefore, time between interruptions must not be included when extracting the time constant from the data trace. The time constant can then be calculated by combining the segments of the data trace where pressure in the tank is rising (figure 3), and then determining the time that elapsed between the time that pressure equals 0 and $.6321(P_s)$, $.6321(P_s)$ and $.8646(P_s)$, and $.8646(P_s)$ and $.9502(P_s)$. P_s denotes the final pressure measured inside the tank, which is equal to subject subglottal pressure. Determination of the time constant is slightly complicated due to natural leaking from the tank. This was corrected by beginning the measurement of a time segment at the highest voltage reached in the previous segment.

It was not possible to measure the first time constant, as the tank was pre-pressurized to 3.5 cmH₂O to facilitate pressure increase to subject P_s during the trial. Therefore, either the second (time between .6321(P_s) and .8646(P_s)) or the third (time between .8646(P_s) and .9502(P_s)) time constant was used. While it was preferable to use the second time constant, this was not always possible. At low subglottal pressures, the pre-pressurization of the tank surpassed the pressure of the first time constant, precluding measurement of the time from the first to second time constant; in these cases, the time from the second to third time constant was measured.

Validation of the method using a computer model

The method was validated by constructing a computer model based on an electrical circuit. This model assumes a linear relationship between pressure and airflow. A higher order function is required at pressures above approximately 40 cmH₂O and airflows above 1200 ml/s as demonstrated by Jiang and Titze (21), but this experiment required subjects to phonate at a comfortable level. The simulated data were sampled at 10 kHz, and low-pass filtered in an identical manner to the subject data. Values of resistance (variable), initial pressure (3.0 cmH₂O), and final pressure (7.0 cmH₂O) were inputted into the model. The data analysis program was then used to measure resistance by determining the time constant. Inputted values of resistance ranged from 10 to 50 cmH₂O/l/s. This simulation closely approximated an actual trial conducted by a human subject (figure 4).

RESULTS

Human subject testing

Data were collected from 20 subjects, each of whom completed 10 trials. Mean laryngeal resistance for all subjects was 22.61 ± 8.65 cmH₂O/l/s (range: 8.73 to 37.12). Data for individual subjects can be seen in figure 5. Mean subglottal pressure was 6.91 ± 1.94 cmH₂O (range: 4.33 to 10.35), and mean aerodynamic power was 0.247 ± 0.170 kPa * l/s (range: 0.102 to 0.440).

Validation using a computer model

Data acquired during the computer model simulation can be seen in figure 7. The estimated laryngeal resistance values recorded in the table represent means from five trials at each inputted resistance. Measurement error increased slightly between estimations made using the first to second time constant ($R^2 = .9999$) to using the second to third time constant ($R^2 = .9997$). This corresponds to an increase in percent error from 1.71% to 1.84%.

DISCUSSION

This study presented a new method used to extract multiple aerodynamic parameters from a single subglottal pressure data trace. Data obtained from a computer model provide support for the validity of this technique, as estimates made using our method showed strong concordance with model input values. The model assumed a linear relationship between pressure and airflow, which has been shown to exist in a range up to 40 cmH₂O and 1200 ml/s (21). Even in pathological phonation, such extreme aerodynamic parameters would not likely be observed. Reliability and practicality were evaluated using human subject testing, which yielded values of R_L comparable to those reported by Jiang et al., who used mechanical interruption to obtain a mean R_L value of 27.9 ± 18.0 cmH₂O/l/s (22).

The airflow redirection technique showed initial promise as a method of measuring P_s , producing both accurate and consistent results (17). Because the redirection tank acts as a capacitor, its time constant can be extracted from the P_s data trace. This requires no additional action on the part of the subject and allows for the indirect calculation of laryngeal resistance,

airflow, and aerodynamic power. Previously, measurements of laryngeal resistance or aerodynamic power required the measurement of both P_s and airflow.

Because R_L and aerodynamic power are being indirectly estimated, there is potential for measurement error. In the case of a subject having a low P_s , it was common for the first time constant to be surpassed simply with the pre-pressurization of the tank. In this case, the time from the second to third time constant was measured, but was somewhat more variable due to artifact in the data near P_s and tank pressure equilibrium. However, as demonstrated in the computer simulation, this measurement error remained small (1.84%). This simulation validated the experimental method, but additional studies could strengthen the method by comparing indirectly estimated R_L values obtained using a time constant to values directly obtained using simultaneous airflow measurement and invasive subglottal pressure measurement via tracheal puncture. Enhancing the proposed method by further evaluating its validity could be the subject of future research.

Aerodynamic assessment of laryngeal health offers the clinician an objective, quantitative tool. Perceptual evaluation of acoustic signals is clinically valuable, but requires raters to have extensive experience, and judgment may differ considerably even among experienced raters (23). By combining acoustic assessment with aerodynamic assessment, a more complete picture of vocal function can be obtained, taking into account both subjective and objective parameters of the voice. Previous limitations of many aerodynamic testing techniques such as extensive calibration of the apparatus or the need for subject training were not encountered in this study, emphasizing the potential impact this method could have if applied routinely in the clinical setting. As measurements of laryngeal resistance and aerodynamic power have been shown to be dependent upon laryngeal health (22,24), routine measurement could provide one means of screening for laryngeal pathology. The method, which can also theoretically be applied to measure airflow (eq. 12), could provide the clinician with a complete report on laryngeal aerodynamic function during sustained phonation in one trial using only a single measurement sensor.

CONCLUSION

A new method was proposed to indirectly estimate laryngeal resistance from a subglottal pressure data trace by extracting the time constant, τ , of the airflow redirection tank. While this experimental system has previously only been used to measure subglottal pressure, we demonstrate the ability to extract parameters of laryngeal resistance, aerodynamic power, and airflow without altering the experimental method. This has potential clinical significance, as it provides a simple means of measuring multiple aerodynamic parameters in a single trial.

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Figure 1. Ideal circuit equivalent of the airflow redirection system. P_s – subglottal pressure; C – capacitance; R_L – laryngeal resistance; R_{Bleed} – natural leaking of the tank.

Figure 2.

A schematic of the experimental system. Solid lines indicate electrical connections, while dashed lines indicate pneumatic connections.

Figure 3. Simulated data traces demonstrating that without the time between interruptions, the three interruptions can be condensed into one interruption. This results in a capacitive curve.

Theoretical Model of Actual Subject Trace

Figure 4. Simulated data trace compared to actual subject data trace with equal subglottal pressure and laryngeal resistance. The simulation used to validate the method of data analysis closely approximates actual trials.

Figure 5.
Box plot of laryngeal resistance (R_L) for each subject.

Figure 6.
Box plot of aerodynamic power for each subject.

Figure 7.

Validation of the data analysis program using a theoretical model of varying resistances. Measurements were made using both the first to second ($R^2 = .9999$) and second to third time constants ($R^2 = .9997$).