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LARYNGEAL MODELING : TRANSLARYNGEAL PRESSURE FOR A MODEL WITH MANY GLOTTAL SHAPES

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ABSTRACT

Voice quality is dependent on the shape and amplitude of the laryngeal airflow signal. Physiological models of the airflow need laryngeal pressure-flow-geometry information. A comprehensive translaryngeal pressure-flow equation is offered. A model of the larynx 7.5 times life size was used with 63 combinations of glottal angles and diameters. The translaryngeal pressure-flow data were nondimensionalized into a pressure coefficient P* and Reynolds number Re such that $P^* = (A_1/Re) + A_2$. A_1 and A_2 were empirically determined from the data, and were structured on Poiseuille, diffuser, and optimum pressure recovery considerations. For pressure drops ranging between 3 and 50 cm H_2O, the average mean difference between the equation predictions and the empirical data was 4.45% (sd 3.38%). The results can be used in phonatory models or speech synthesis schemes for which volume velocity is dependent upon subglottal pressure and glottal configureation.

INTRODUCTION

Synthesis and coding of spoken language require decisions regarding the salient characteristics of the laryngeal sound source. During a phonatory cycle, continual change in glottal configuration [1] is accompanied by changes in glottal resistance to flow and intraglottal pressures [2][3][4][5][6]. The vocal folds are partially driven by the glottal air pressures, and the volume velocity is dependent on the subglottal pressure and laryngeal resistance. [Here the quasi-steady interdependence of pressure-flow-geometry is assumed.] In this study, translaryngeal pressure and airflow were related to specific glottal geometries. The resulting equations can be applied to synthesis and coding schemes in which laryngeal volume velocity is an important variable.

The study here augments the existing static model results for steady flow laryngeal fluid mechanics. The work by van den Berg et al. [2] and Ishizaka and Matsudaira [3] established a basis for exploring the pressure-flow relationships throughout the various regions of the larynx, from glottal entry to the hypopharynx. The various terms for pressure change in the inferior to superior direction add up to a translaryngeal pressure approximation.

The pressure can also be expressed as the translaryngeal pressure coefficient. This term expresses the dimensional translaryngeal pressure drop (in cm H_2O, for example) in terms of the dynamic pressure estimated at the minimal glottal cross sectional area. The dynamic pressure is defined as one-half times the density of air times the squared velocity of air flowing through the minimal glottal location. The velocity is usually taken as the volume flow (in cubic centimeters per second) divided by the cross sectional area (in centimeters squared).

METHODS

The larynx models created for this project are collectively referred to as model M5. They were larger than normal (prototype) size by a factor of 7.5. This size was chosen in order to provide relatively small and measurable glottal diameters.

Model M5 consisted of a rectangular airway within which were placed two simulated vocal folds. Each vocal fold was precisely milled by a digital mill to specifications as follows (given in prototype size): The glottal thickness was 0.3 cm and length 1.2 cm. The vocal fold glottal surface was flat, and the radii of curvature for the lower and upper "lips" are indicated in Table 1. The radii for the upper glottal "lip" were estimated by inspection of schematics of vocal fold frontal sections and were determined by the expression Ru = Ro / (1-sin[b/2]), where Ru is the radius of the upper "lip", Ro is the radius of the upper "lip" when the vocal folds form a uniform duct, and b is the included glottal angle which ranges between 40 degrees divergence to -40 degrees convergence. The authors felt that this specification created a realistic vocal fold contour. Refer to Figure 1 for a schematic of the vocal fold for three included angles, -40, 0, and 40 degrees. As seen in Figure 1, the vocal fold surface converges from the tracheal side at a 40 degree angle, has a lower "lip" radius of 0.15 cm, continues superiorly with a flat surface, has a variable upper radius depending upon the included

Table 1. Radii (in cm) of curvature for the upper margin of the vocal fold pieces used in the larynx model. The lower margin radius was 0.15 cm in prototype units.

Glottal Angle	Upper Lip Radius
-40 (conv)	0.0735
-20 (conv)	0.0841
-10 (conv)	0.0908
-5 (conv)	0.0946
0 (uniform)	0.0987
5 (div)	0.103
10 (div)	0.108
20 (div)	0.119
40 (div)	0.150

angle, and has a flat superior surface.

Two matching vocal fold pieces were attached to the sides of the airway box by screws. The included angle between the two vocal folds was determined by the choice of vocal fold configuration. The minimal diameter between the vocal folds was determined by the choice of shim placed between one vocal fold and one side of the airway box.

Figure 2 is a schematic of the airway. The box, vocal fold pieces, and entry convergence upstream of the trachea were made out of plexiglas. The sections of the airway upstream and downstream of the vocal folds were both rectangular, with a lateral width of 2 cm when the maximum glottal diameter (.32 cm) was used. The anterior-posterior dimension of the upstream and downstream airway was 1.2 cm, the same as the glottal length.

Pressure taps were located 0.16 cm upstream of the start of the vocal fold piece, and 3.1 cm downstream of the vocal folds. Both pressure taps

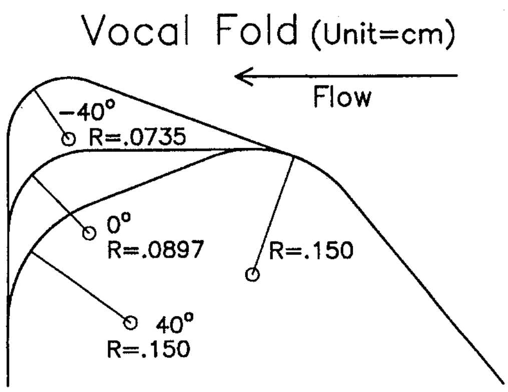

Fig. 1 Outline of the vocal fold shapes for included angles of -40 degrees (glottal convergence), 0 degrees (uniform glottis), and +40 degrees (glottal divergence). The radius of the upper glottal margin decreases with less divergence and greater convergence.

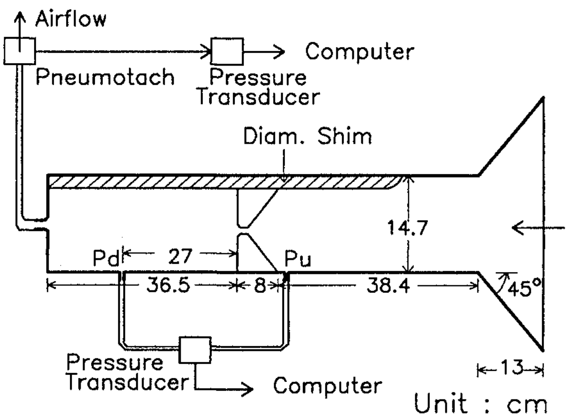

Fig. 2 Schematic of the experimental set-up.

were in the side of the airway box on one side only. The pressure drop between these two locations was termed the translaryngeal pressure drop and measured by Validyne pressure transducers (Mp45, DP103). The airflow was created by suction downstream of the model. A pneumotach system (Hans Rudolph 3719, 4813) within the downstream section was used to measure the airflow.

After a chosen vocal fold configuration was set in the airway box, a sequence of airflows was drawn through the box. For the 63 configuration cases (angles of -40, -20, -10, -5, 0, 5, 10, 20 and 40 degrees, and diameters of approximately 0.005, 0.010, 0.02, 0.04, 0.08, 0.16 and 0.32 cm), a total of 2295 pressure-flow values were obtained. Each pressure and flow measurement was recorded by digitizing at 20K samples per second a one second period of the voltage outputs for both the pressure drop and airflow, taking the average across the one second intervals, applying the calibration conversions, and storing the values into appropriate data files.

The size enlargement required the translaryngeal pressure drop to be less than in the prototype size by a factor of the inverse of 7.5 squared, and the model flows to be larger than in the prototype by a factor of 7.5. These ranges were measureable by the transducers over the prototype ranges of 0.01 to 388 cm H_2O and 0.9 to 735 cc/s. The inaccuracy of both pressure and flow measurement was a maximum of approximately +/- 4% from all sources (multiple transducers, multiple calibration devices, and repeatability over time). For purposes of error calculations, the following errors of measurement were estimated: pressure, 3%; flow, 3%; area, 1.3%; density, 0.5%; and viscosity, 0.5%. Given these error estimates, the pressure coefficient had an error of approximately 5.5%, and Reynolds number (2 times the volume flow divided by half perimeter times viscosity) approximately 3.5%.

RESULTS AND THE S-G EQUATION

Figure 3 illustrates an (excellent) example of curve fitting performed on each of the 63 laryngeal configuration cases. The figure illustrates a fit of data for the case of a uniform glottal duct with a diameter of approximately 0.01 cm. The data in nondimensional form (pressure coefficient, P*, versus Reynolds number, Re) were graphed, and a curve of the form

$$P^* = (A_1/Re) + A_2, \qquad (1)$$

where A_1 and A_2 are coefficients, was fit to the data by eye such that the fit was best between 1 and 50 cm H_2O. Equation (1) is the typical form for the relationship between pressure coefficient and Reynolds number for orifice and pipe flows, and emphasizes the viscous dependence at low flows and turbulent dependence at high flows. Values for the A_1 and A_2 coefficients were obtained for each of the 63 cases.

GENERAL EQUATION

For the general S-G Equation, $P^* = (A_1/Re) + A_2$, A_1 and A_2 were nondimensionalized and determined with fluid mechanics considerations. The following laryngeal geometry ratios were used: Aspect Ratio, $R_a = L_g/D_g$; LT Ratio, $R_{lt} = L_g/T_g$; and DT Ratio, $R_{dt} = D_g/T_g$, where L_g is the glottal length, D_g the minimal glottal diameter, and T_g the glottal thickness.

When the Poiseuille expression for uniform duct flow is manipulated, the resulting nondimensional pressure has an R_a term multiplied by an $(R_{lt} + R_{dt})$ term. As given below, the A_1 parameter, associated primarily with viscous pressure losses, receives this term. This term is modified to account for nonuniform glottal ducts following an inverse tangent relationship suggested by Idelchik ([7], p. 199). The A_2 term is related to kinetic pressures, and in the

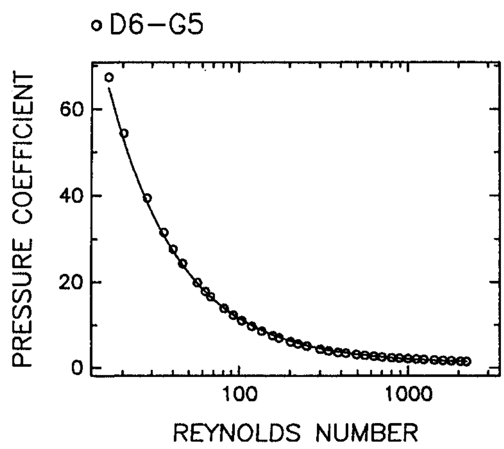

Fig. 3 The excellent fitting of $P^* = (A_1/Re) + A_2$ to data (uniform glottis, diameter = 0.00805 cm).

formulation below is related to the aspect ratio, glottal angle, and the DT ratio. The quotient expression for A_2 is (our) calculation made from rectangular diffuser behavior for optimum recovery as given by Miller ([8], p 28).

The general S-G Equation is given as follows:

$$P^* = (A_1/Re) + A_2,$$

where

$$A_1 = R_a^{0.472}(R_{lt}+R_{dt})^{3.31}$$

$$1/[C_1 \ |tan(0.33X)|^{0.8} + 1] + C_2 tanX$$

$C_1 = -16 log(R_a) + 64$, and
$C_2 = 60/log(R_a) + 25$, for X(angle) >= 0,

$C_1 = 30 log(R_a) - 19$, and
$C_2 = 55/log(R_a) - 130$, for X(angle) < 0,

$$A_2 = 0.97 - 0.00074R_a -$$

$$0.04R_a/[(X - 10R_{dt}^{0.09})^2 + 15].$$

The restriction for small diameter:

if $R_a > 12{,}000$: $A_1 = 7650$, for X(angle) >= 0
$A_1 = 2000$, for X(angle) < 0

if $R_a > 240$: $A_2 = 0.15$

In the important range of 3 to 50 cm H_2O, the average difference from the data is 4.45% (s.d. 3.38%).

DISCUSSION

The S-G Equation can be used to predict translaryngeal flow given specific values for transglottal pressure and glottal geometry. The equation was based on data from a physical model with a wide range of glottal angles and diameters, perhaps the most important geometrical variables, and a fixed glottal length, thickness and downstream shape (there were no ventricular folds). The nondimensional nature of the equation may allow some deviation of values for the glottal length and thickness.

The nondimensional pressure coefficient for translaryngeal pressure is not constant. The data and S-G Equation indicate that it can range up to 150 for a uniform glottis and low translaryngeal pressure, to consistently less than 1.0 for large diameters and high pressures.

Figure 4 shows a comparison among three equations that predict laryngeal volume velocity. Ishizaka [9] modified the Ishizaka and Matsudaira [3] turbulent equation to account for losses due to area changes in the glottis, and we use the value of 1.0 for his eta term. The simplest way to estimate the pressure coefficient for modeling is to assume it has a constant value (e.g., [10]), and 1.1 is used here. The S-G Equation is also used in Figure 4 to predict the volume velocity. Hirano [1] published a schematic of glottal geometries having 10 phases during one cycle of phonation. These geometries were measured for angle, and Figure 4 represents an interpolation between these angles for a constant translaryngeal pressure.

Figure 4 suggests that up to and slightly beyond peak flows, the S-G Equation predicts the highest flows, with the Ishizaka and Matsudaira equation predicting not only a relatively lower peak but also a broader peak. The constant k value expression predicts an underestimation of the flow after the peak flow, but the slowest "shut off" of the flow. The Ishizaka and Matsudaira equation predicts the fastest "shut off" of the flow. Acoustic effects will be examined later.

The advantage of the S-G Equation over existing equations is that it is based on empirical measurement for a wide variety of glottal angles and diameters.

CONCLUSION

This study offers a general equation to predict translaryngeal volume velocity for given glottal angles, diameters and translaryngeal pressures. The equation was based on fluid mechanics considerations and data analysis of a plexiglas model of the larynx with well defined entrance and exit radii.

The S-G Equation given in this report can be used for theoretical and practical studies. The equation can be used when relatively sensitive changes in glottal flow are required, and also for testing the accuracy of numerical analysis models of laryngeal flow. Acoustic effects will be examined later.

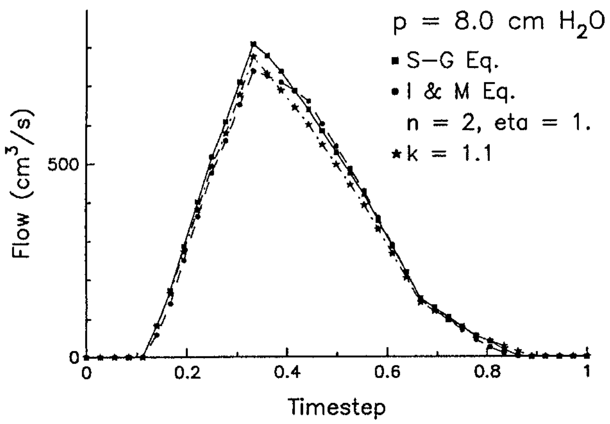

Fig. 4 Comparison of volume velocity values during one phonatory cycle based on glottal configurations by Hirano [3]. "I & M Eq." refers to the equation used by Ishizaka [9].

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