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II. TECHNICAL PHONIATRICS

A. AERODYNAMIC MEASUREMENTS IN AN ENLARGED STATIC LARYNGEAL MODEL

Binh N.*. and Gauffin J.

Abstract

A static model of the larynx scaled to five times the real size has been constructed. The magnified scaling enables accurate and reliable measurements to be made of the pressure distribution inside the glottis as well as observations of the flow patterns by means of the Schlieren method. The model has parallel walls and approximates in two dimensions the cross-section of the laryngeal airway.

Although the model is static and only has an approximate shape of the real larynx, it can give useful information on the aerodynamic forces inside the glottis which cannot be accurately described by present theories. Measurements of flow and pressure have been made for various configurations of the glottal opening approximating observed cross-sectional shapes of the vocal folds during different phases of the vibratory cycle. These measurements have revealed the significant magnitude of the forces on the lower edges of the vocal folds.

In order to compare measured data with published data, the entry and exit loss coefficients in particular have been calculated. The loss coefficients are not constant but vary with both the flow and glottal geometry in a rather complex way.

Introduction

Forces resulting from the pressure distribution over the surface of the vocal folds together with the stress and momentum forces determine the modes in which the vocal folds move in phonation. The pressures on the fold surfaces push them apart (positive pressure) or pull them together (negative pressure). Our aerodynamic theories are not accurate enough to let us calculate these forces for arbitrary vocal fold shapes, so we have to rely on empirical measurements in models.

van den Berg, Zantema, and Doornenbal (1957) performed the first measurements of the pressure within the glottis and the estimated glottal resistance on a mould made directly from a human larynx. Since their experiment (about 25 years ago), no attempt has been made to carry out similar experiments to check the reliability of the produced results. The practical difficulties in making small moulds from the human larynx and the tediousness in collecting data from such small scale moulds have probably discouraged many people.

The theory on the vibration of the vocal folds, proposed by Ishizaka and Matsudaira (1968, 1972 a,b), casts new lights on the findings of van den Berg et al (1957). In fact, the theory modifies to a great

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extent some of the results so far accepted as standard. One of these is the loss coefficient for the airflow into and out of the glottal constriction. The value 1.37 of the entry loss coefficient, given by van den Berg et al., is accepted by Ishizaka and Matsudaira but the exit loss coefficient of -0.5 is subject to modification. The two-mass model of Ishizaka and Matsudaira (1972) is perhaps the most extensive theoretical study of the mechanical function of the larynx. The two-mass model, however, does not take into account the aerodynamic properties of the flow which involve such important factors as flow separation, turbulence and other irregularities pertaining to the complex process of airflow. Especially when the glottis has a diverging shape, the flow is very unstable and flow separation is inevitable for flow conditions and dimensions of the glottis in phonation.

The experiments described in this report were designed to study the flow of air for various shapes of the glottis. It is well known from high-speed films of the vibrating vocal folds that in one cycle of vibration, the glottal opening assumes a number of basic shapes. The sketches in Fig. 1, adapted from Hiroto (1980), show in frontal view the change in glottal shape as the vocal folds vibrate through one cycle in the chest register. From aerodynamic points of view, it is definitely vital to examine the flow conditions and patterns for each of these glottal shapes. Three basic shapes can be depicted from the sketches: parallel, converging, and diverging. In this report the terms 'uniform' and 'non-uniform' glottis are used to denote parallel and converging/diverging glottis, respectively. The function of the ventricular folds on the flow was also studied by means of pressure measurements and flow visualization.

Description of the model

The model of the laryngeal system used in this study is essentially a rectangular duct with various constrictions. The model has been made five times as large as the life size to enable more accurate measurements of pressure within the narrow glottis. The actual dimensions and proportions of these constrictions have been adapted from X-ray planigrams of the larynx in phonation in the chest register which show rather thick vocal folds (van den Berg, 1968). The folds are constructed bilaterally symmetrical. Each fold is divided in depth (thickness) into an upper and a lower part in the same way as the two-mass model used by Ishizaka and Flanagan (1972). These four parts (two on each fold) can be
Fig. 1. Schematic representation of eight instantaneous stages in one vibratory cycle of the vocal folds. Adapted from Hiroto (1980).
laterally adjusted independently of each other to produce numerous
glottal shapes. In contrast to the two-mass model, this model is static,
and the vocal folds are not permitted to move or vibrate during tests.
All sharp corners and discontinuities on the fold surfaces were carefully
smoothed out or filled up with plasticine.

A slight modification to the angle which the folds make with the
vertical line in the frontal view produces two basic static laryngeal
models tested in this study. Schematic diagrams of the two models are
shown in Fig. 2. In Fig. 2(a), the folds are perpendicular to the vertical,
representing the larynx at rest, i.e., not in phonation. Moulds
that are made from a larynx at rest will have more or less this form.
In Fig. 2(b), the folds are at an angle of 65 degrees with the vertical.
This angle is to simulate the effect of the increased subglottal pres-
sure during phonation which tends to push the vocal folds upwards.
The angle has been approximated from X-ray films of a male larynx in phona-
tion in the chest register (van den Berg, 1968). Model 2(a), which
subsequently will be called the ‘straight model’, is used mainly to
obtain data for comparison with published data taken from similar mod-
els. Model 2b, called the ‘angled model’, on the other hand, was used
for all test purposes.

Airflow was provided by a fan drawing air through the system. The
volume flow capacity range was from 0 to 50000 cm$^3$/s. Pressure tap holes
with a diameter of 1.0 mm were provided in the trachea and the pharynx
to measure subglottal and supraglottal pressures. Pressure holes of the
size 0.5 mm in diameter were drilled through the vocal surfaces. The
holes were arranged in such a way that no hole lies directly behind
another in the flow direction in order to reduce possible disturbances
induced in an upstream hole being carried down to a downstream hole
which could result in erroneous pressure readings. In Fig. 4, the
positions of the four pressure holes on each vocal fold surface are
shown. Pressure hole $P_1$ measures the pressure on the lower edge of each
fold, $P_2$ and $P_3$ measure pressures within the glottis, and $P_4$ records
the pressure on the upper edge of each fold. All pressures were recorded
simultaneously. The size of the holes was chosen to provide reliable
pressure readings for glottis openings in the model larger than 3 mm.
For glottal openings smaller than 3 mm, small errors are likely to be
obtained. Rayle (1958) stated that for the ratio (hole diameter/opening
width) up to 0.125, the error is below $+1.2\%$ of the dynamic pressure.
For a higher ratio the error was empirically determined by Ray (1956)
Fig. 2. Details of the two laryngeal models.

Fig. 3. Schematic layout of the laryngeal model and auxiliary components.

Fig. 4. Arrangement of pressure holes on the two sections of the vocal fold.
and given by the expression \(0.58 \text{Re}^{-0.75}\), which means that the error is dependent on Reynolds number. Thus, an error of about +3% can be expected at a glottal width of 1 mm in our model. The pressure holes were carefully prepared to eliminate irregularities. Special care was taken to ensure that the holes were flush with the surface.

The sides of the models were made of high-quality glass so that registrations of the flow patterns could be made by the Schlieren optical technique.

Fig. 3 shows the schematic layout of the various components. From the right, the entry duct to the trachea is about 30 cm long and had the main function of providing a straight and smooth airstream into the glottal system. To achieve this, a round entry was provided with an aluminum honeycomb of 8 cm length and two fine wiregauzes to break down any turbulent eddies introduced at entry. The airstream thus entering the glottis was essentially undisturbed. The transition between the trachea and the glottis being a contracting rectangular duct accelerates the air into the narrow glottis. The pharynx consisted of a 20 cm long duct on which the two ventricular folds, or false vocal folds, were situated. These ventricular folds are removable.

**Method of investigation**

The pressure distribution across the vocal folds was studied by measuring the static pressures at different positions across the surface. The subglottal pressure was measured at a point 6 cm from the entry to the glottis, situated upstream from the contracting section of the trachea. Pressures were measured by two Betz micromanometers and the flow was measured by the "orifice in the pipe" method. The flange diameters were 34 mm and 16 mm and the pipe diameter was 45 mm. The pipe was mounted downstream from the test section and Betz manometers were used to measure the differential pressure. In the later part of the experiment, pressure transducers and charts were used instead. The two methods were compared and gave almost identical results.

For every pressure point and glottis configuration a maximum number of ten readings were taken on each vocal fold for ten different fan speeds. Each reading in turn was read twice or more depending on the degree of fluctuation of the pressure values. The final pressure values tabulated and used in graphs are, therefore, the average values of at least four readings. In the case of the exit loss coefficient, because of the scattering of the data, all readings of pressure are shown on
the graphs to illustrate the degree of uncertainty.

The upper and lower parts of the folds were adjusted to provide various glottal shapes. For uniform glottis, the glottal opening size ranges from 1.0 mm to 10 mm, which is equivalent to 0.2 mm to 2.0 mm in a real size model. The volume flow was varied from 20 to 1000 cm$^3$/s. For non-uniform glottis converging and diverging glottal shapes were tested. The entry glottis dimension, $W_1$, and the exit glottis dimension, $W_2$, are used to denote the degree of convergence or divergence.

The flow pattern was studied by means of the Schlieren optical technique.

**Scaling of the data**

The model used in this investigation is five times the real size. However, the data presented in this paper have been scaled down according to the dynamic similarity principle. This requires the same Reynolds number in both cases. The Reynolds number in this report is defined as:

$$Re = \frac{V_g W / \nu}{U_g / \nu} = \frac{V_g}{U_g / \nu}$$

where $V_g = U_g / A$ and $A = 1 / W$

$W$ = glottis width, $l$ = glottis length

Since the kinematic viscosity, $\nu$, is the same in both cases we can write:

$$U_{gp} = U_{gr} \cdot \frac{l_r}{l_p}$$

where $p$ refers to the present model and $r$ to a real size model.

With $l_r / l_p = 1/5$, we obtain:

$$U_{gr} = U_{gp} / 5$$

Thus, the volume flow in the scaled-down model corresponds to $1/5$ of the volume flow in the present model. A similar analysis can be made for the scale factor of the pressure and this will give the result that the pressure values should be multiplied with 25 in the scaled-down model.

It should be noticed that the scaled-down length of the glottis is 24 mm instead of the more realistic length 18 mm. When comparisons are
Results and discussion

Pressure drop versus flow

Fig. 5a shows pressure drop, $P_d$, as a function of volume flow, $U_g'$, for the uniform glottis with the glottal width, $W$, as parameter. The two different models are compared in this figure. It can be observed that the pressure drop in the angled model is slightly higher for the same volume flow.

van den Berg et al (1957) gave the following expression for the pressure drop, $P_d$, across the glottis:

$$P_d = (0.9 + \frac{24T_v}{gW^2}) \cdot \frac{\frac{U_g^2}{gW^2}}{2}$$

where $g$ is the density of air, $T$ glottal thickness, and $W$ glottal width.

Ishizaka & Matsudaira (1968) proposed two expressions for the translaryngeal pressure drop.

The laminar equation:

$$2P_g V_g^2 = 20 T_v / g W^2 + 2.2 \sqrt{\frac{T_v V_g W^2}{g}} + 1 - 2N(1-N)$$

$$P_d = (1-2N(1-N) + 2.2 \sqrt{\frac{T_v}{g W^2}} + 20 \cdot \frac{T_v}{g W^2}) \cdot \frac{\frac{V_g^2}{g W^2}}{2}$$

The turbulent equation:

$$2P_g V_g^2 = 24 T_v / g W^2 + 1.375 - 2N(1-N)$$

$$P_d = (1.4-2N(1-N) + 24 \cdot \frac{T_v}{g W^2}) \cdot \frac{\frac{V_g^2}{g W^2}}{2}$$

The curves of $P_d$ versus $U_g$ for van den Berg's equation and the turbulent equation of Ishizaka & Matsudaira are plotted in Fig. 5b together with our data.

Fig. 6a and 6b show the variation of $P_s$ with $U_g$ for the case of non-uniform glottis. For small glottis openings, as in Fig. 6a with $W = 0.4$ mm, the subglottal pressure remains fairly constant as the shape of...
Fig. 5(a). Subglottal pressures (or translaryngeal pressure drop) as a function of volume flow for uniform glottis. Broken curves: angled model. Continuous curves: straight model.

Fig. 5(b). Data curves (---) for subglottal pressures in relation to volume flow for uniform glottis and angled model compared to curves calculated from van den Berg's equation (---) and from Ishizaka and Matsudaira's turbulent equation (- - -).
Fig. 6(a). Volume flow varies with subglottal pressure for glottis with varying exit dimension and constant entry dimension. \( W_1 = 0.6 \text{ mm.} \) + calculated from two-mass equation by Ishizaka and Flanagan (1972).

Fig. 6(b). Volume flow varies with subglottal pressure for glottis with varying exit dimension and constant entry dimension. \( W_1 = 0.6 \text{ mm.} \) + calculated from two-mass equation by Ishizaka and Flanagan (1972).

Fig. 6(c). Comparison of volume flow for three glottis configurations. From left to right: uniform, diverging, and converging. Common minimum opening is 0.6 mm.
the glottis becomes more diverging with the same entry dimension, except at high volume flow. This is due to the fact that the flow of air through the lower narrow part of the glottis is jet-like and separates completely from the walls in the upper part of the glottis. Changing the upper glottal dimension in this case has little effect on the jet stream of air coming from the lower part of the glottis. As the exit dimension of the glottis widens, however, $P_s$ depends more and more on the glottal geometry which can be clearly seen from Fig. 6b. In Fig. 6a and 6b, a number of points are calculated with the two-mass model proposed by Ishizaka & Flanagan. The two-mass model predicts lower pressure drop for a glottis with small entry dimension. For larger entry dimensions, the predicted values agree rather well with the present data.

If the curves 0.6/0.6, 1.0/0.6, and 0.6/1 in Fig. 6a and 6b are compared in Fig. 6c, we can see that the converging shape has the lowest flow resistance and the uniform has the highest. However, the difference is not great and as a good approximation we can use the minimum area for calculation of the flow in the non-uniform glottis.

**Pressure distribution in the glottis**

There may be a pressure variation along the vocal length (transversely), especially in the real glottis because the opening width varies along the folds. However, in this study only the pressure across the fold thickness (in the direction of the flow) was investigated.

For uniform glottis, the pressure variations for various glottal dimensions are shown in Fig. 7a to 7d with $P_n$ (n=1,2,3,4) indicating pressures measured at the four different positions inside the glottis, e.g., at the lower edge, within the glottis, and at the upper edge. The data points follow approximately straight lines showing that the pressures vary almost linearly with the translaryngeal pressure drop. For small glottal openings, as in Fig. 7a, the pressure at point P1 and P2 is positive while the pressure at P3 and P4 is slightly negative. When the glottis becomes wider, as in Fig. 7b to 7d, the pressures at the entrance of the glottis change sign and become negative.

In Fig. 8, similar curves for diverging and converging glottal shapes are shown. If we compare the converging and the uniform glottis with the same minimum opening, we can see that the converging shape produces higher and positive pressures at P1 and P2 on the lower part of the folds, while the pressure at P3 and P4 on the upper part of the vocal folds is still low in magnitude. The configuration in Fig. 8a and
Fig. 7. Straight lines approximating measured pressures along the glottis in relation to the translaryngeal pressure drop. Uniform glottis.
8b is typical for the opening phase of the glottal vibratory cycle. The effect of the positive pressure is to push further open the lower edges of the folds, while the upper edges are following with a lag in phase. This trend is reversed when the glottis assumes a diverging shape, as in Fig. 8c and 8d, typical for the closing phase of the glottal cycle. In this case, $P_1$ and $P_2$ are both high and negative, while the pressures on the upper part remain insignificant in magnitude. The negative pressure draws the lower edges of the folds together, forcing the glottis to close. It is significant that both in a narrow and a wide glottis, the driving forces on the vocal folds are mainly acting on the lower edges of the folds. The upper edges seem to be driven by mechanical coupling only, and therefore they follow the lower edges with a lag in phase. The change of glottal geometry during the vibratory cycle seems to be essential for the energy transfer from the airflow to the vibrating vocal folds which, in turn, is necessary for maintaining the vibration.

Our data apply to static glottal conditions, i.e., when the folds are not in vibration. In the dynamic case, however, the acoustic load of the vocal tract and the trachea have the effect of delaying the flow relative to the area variation (Fant, 1982). This will lower the flow during the opening phase and increase the flow during the closing phase relative to the static case. However, if a vibratory cycle of the folds is broken down into momentarily static stages, a first approximation of the time-varying forces inside the glottis can be computed. Consider a cycle of vibration schematized in the sketches, adapted from Hiroto (1980) and shown in Fig. 1. At the opening phase, stages 1, 2, 3, the glottis is converging in shape. Outward forces are then acting on the lower edges, pushing the folds apart, and the forces at the upper edges are small. At stages 4 and 5, the glottis is more or less uniform in shape, in which case negative pressures appear on the lower edges and the folds begin to close there first. As the folds enter the closing phase, the glottis becomes diverging (indicated in stages 6 and 7), and a more negative pressure is applied on the lower edges, forcing the folds to close. The aerodynamic forces seem to act, during most of the vibratory cycle, in the direction of the movement of the vocal folds, thus effectively transferring energy from the flow to the vibrating folds.

The pressure on the lower edges of the folds is a function of both the widths $W_1$ and $W_2$ of the lower and the upper sections of the glottis. In Fig. 9, curves are drawn for $P_1$ versus $W_1$ with $W_2$ as parameter. A
Fig. 6. Straight lines approximating measured pressures along the glottis in relation to the translaryngeal pressure drop. Non-uniform glottis. (a) and (b): converging, (c) and (d): diverging.
Fig. 9. Pressure $P_1$ at the lowest point inside the glottis plotted as a function of the width of the lower section ($W_1$) and the upper ($W_2$). Broken curves are extracted from Stevens (1977) which were calculated from formulae proposed by Ishizaka and Matsudaira (1972a,b). Subglottal pressure = 8 cm $H_2O$. Note that Stevens' curves have been modified slightly to suit the dimensions of the models.
subglottal pressure of 8 cm H₂O was used. These curves can be compared with those given by Stevens (1977) which were based on calculations of pressures and flows using procedures proposed by Ishizaka & Matsudaira (1968). It can be observed that Stevens' curves show much higher negative pressures for all cases and the pressure minima occur at a lower \( W_1 \) value. This implies that there will be strong forces applied to the glottal walls at the last stage of the closing phase, which can result in high collision forces between the two folds, a phenomenon which would be unlikely to occur in phonation. The data curves, on the other hand, exhibit gentler slopes and the magnitudes of the pressure on the lower edge is not as large. The theoretical curves approach zero as the glottis becomes parallel (uniform). The data curves, however, do not agree with this trend, especially not at large glottal openings.

The minima of the theoretical curves appear almost at the same inferior diameter or in a very small range of this diameter. The minima of the data curves, on the other hand, occur when the glottis has a gentle diverging shape. The difference between theoretical and data curves could be due to various aerodynamic factors.

The pressure distribution in the glottis is shown in Fig. 10 for three glottal shapes at a pressure drop of 8 cm H₂O.

**Entry loss coefficient**

From the trachea, the air is accelerated through the contracting duct into the narrow glottis. At the entry to the glottis, the air moves from a large to a small area, its particle velocity increases sharply and, consequently, there will be a sharp drop in pressure. This pressure drop is known to be proportional to the dynamic pressure within the glottis,

\[
P_{BL} = \frac{1}{2} \rho V_{GL}^2
\]

The Bernoulli equation applied at entry to the glottis gives:

\[
P_s = P_1 + k_1 \frac{\rho V_{GL}^2}{2}
\]

where \( k_1 \) is defined as the entry loss coefficient and \( V_{GL} \) is the particle velocity in the lower section. From this equation

\[
k_1 = \frac{P_s - P_1}{2 \rho V_{GL}^2}
\]

The entry loss coefficient has been studied by van den Berg et al (1957) and given an average value of 1.37, which has been accepted in
Fig. 10. Pressure distributions along the glottis for the three glottal shapes. Note that the straight lines do not imply that the pressures vary linearly between the points.
calculations of pressures and flows for the typical geometry and flow conditions in voice production research. In this study $k_1$ was found, however, to be dependent on both volume flow and glottal geometry. To express this dependency, the loss coefficient is plotted against the Reynolds number which in this study is defined as:

$$Re = \frac{V_g W}{\nu} = \frac{U_g W}{A_g \nu} = \frac{U_g}{\nu}$$

where $A_g$ is the glottal area, $W$ is the glottis width, $\nu$ is the kinematic viscosity of the air, and $l$ is the vocal fold length. The Reynolds number defined in this way is directly proportional to the volume flow.

Fig. 11a and 11b show the variation of $k_1$ with $Re$ for the case of uniform glottis. As $Re$ increases, $k_1$ decreases for all glottis dimensions up to $Re=5000$ for this model. For higher $Re$, the loss coefficient stabilizes to an average value of 1.3 to 1.5 for the angled model and 1.4 to 1.55 for the straight model. The average value of $k_1$ is slightly lower for the case of the angled model which has a smoother entry to the glottis.

Below the $Re$ value of 5000, $k_1$ is very sensitive to changes in volume flow. A value of $k_1$ as high as 1.8 can be obtained at a low Reynolds number. Also, it can be observed that the loss coefficient increases as the glottis widens.

For non-uniform glottis, $k_1$ varies in general in the same way as for uniform glottis, that is, $k_1$ decreases as $Re$ increases and stabilizes to an almost constant value beyond $Re=5000$. As the shape of the glottis changes, however, $k_1$ varies accordingly and depends strongly on the geometry of the glottal shape. Fig. 12a-12c shows that $k_1$ depends not only on the lower glottal width $W_1$ but also on the upper width $W_2$. A general characteristic of these curves is that the loss coefficient for a diverging glottis is higher than that for a uniform glottis while the opposite is true for converging glottis.

The entry loss coefficient obtained for both the uniform and the non-uniform glottis in the foregoing discussion is given in the Reynolds number range of 200 to 2000 in this model. In actual phonation, the Reynolds number would lie between 200 and 800, which would give values of $k_1$ between 1.3 to 1.4 depending on the glottis size and shape and the volume flow. Empirical formulae can be developed for the relationship between $k_1$ and $Re$ for both uniform and non-uniform cases. Such relationships would be useful for computer modelling of the larynx.
Fig. 11(a). Variation of entry loss coefficient with Reynolds number for uniform glottis for angled model.

Fig. 11(b). Variation of entry loss coefficient with Reynolds number for uniform glottis and straight model.
ENTRY LOSS COEFFICIENT $k_l$

**Figure 12.** Variation of entry loss coefficient with Reynolds number.
Exit recovery coefficient

As the air escapes from the narrow glottis into the pharyngeal cavity, its high velocity is greatly reduced. The particle velocity of the air in the supraglottal duct is so low that it can be neglected. The Bernoulli equation applied at glottis exit gives:

\[ P_4 + k_2 \frac{gV^2}{2} = P_c \]

where \( k_2 \) is usually defined as the exit loss coefficient, \( V_g \) is the effective particle velocity of the air in the superior section of the glottis, and \( P_c \) is the static pressure in the supraglottal duct which is nearly zero and can be neglected. Thus:

\[ k_2 = -\frac{2P_4}{\frac{gV^2}{2}} \]

The exit loss coefficient obtained is negative which indicates a pressure recovery. This coefficient will, therefore, be called exit recovery coefficient.

Fig. 13 shows the variation between \( k_2 \) and \( R_z \) for both uniform and non-uniform glottis. For the same exit dimension, \( k_2 \) has in general higher values for a converging glottis than for other shapes. This can be explained by the fact that for a converging glottis, the air accelerates near the exit which makes the pressure there lower than in the case of uniform or diverging glottis of the same exit dimension.

The average values for \( k_2 \) are listed in the table below for four exit dimensions tested:

<table>
<thead>
<tr>
<th>( W_2 ) mm</th>
<th>( k_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.05</td>
</tr>
<tr>
<td>0.6</td>
<td>0.06</td>
</tr>
<tr>
<td>1.0</td>
<td>0.09</td>
</tr>
<tr>
<td>1.4</td>
<td>0.17</td>
</tr>
</tbody>
</table>

At smaller diameters the measurements were unstable and, hence, discarded.

It can be seen from the data points that although there is a
Fig. 13. Relationship between the exit recovery coefficient and Reynolds number for various "g" values.

\[
\text{REYNOLDS NUMBER } Re = \frac{V}{M} = \frac{\nu_g}{1/4} x^2
\]
definite pattern for the variation of \( k_2 \) with \( Re \), there is a slight scattering of the data. The models in this study have been constructed largely to facilitate the measurement of pressures especially at exit. The scattering of the points indicates, however, that there are still some uncontrolled factors that influence our measurements. The practical difficulty here may be that the measuring holes are situated quite near the exit and could be influenced by flow separation and pressure and flow conditions just above the glottis.

Theoretical considerations of losses, due to a sudden expansion in a duct, may be calculated with the use of Bernoulli and momentum equations. For a steady, incompressible, turbulent flow the following expression can be derived for the exit recovery coefficient:

\[
k_2 = \frac{2A_g^2}{A_p}(1 - \frac{A_g^2}{A_p})
\]

where \( A_g \) is the area of the upper section of the glottis and \( A_p \) is the pharyngeal area. For the models tested, \( k_2 \) can be expressed as

\[
k_2 = \frac{2W_a}{W_p}(1 - \frac{W_a}{W_p}) = 2N(1-N)
\]

where \( N = W_a/W_p \). \( k_2 \) calculated from this formula is tabulated below:

<table>
<thead>
<tr>
<th>( W_a \text{ mm} )</th>
<th>( k_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.053</td>
</tr>
<tr>
<td>0.6</td>
<td>0.078</td>
</tr>
<tr>
<td>1.0</td>
<td>0.13</td>
</tr>
<tr>
<td>1.4</td>
<td>0.18</td>
</tr>
</tbody>
</table>

These values can be compared with the average experimental values given above. There is a fairly good agreement between theoretical and experimental values.

**Conclusion**

The scaled-up model of the laryngeal system used in this study facilitates the study of airflow in the otherwise small laryngeal airway. This model has made possible a thorough investigation into the aerodynamics of the glottis. Static pressures on the vocal fold surfaces reveal the mechanism of glottal vibration. The results show that the
pressure on the lower edges of the folds plays an important role in the movement of the folds. This pressure is positive for a uniform glottis with small openings (around 0.4 - 0.5 mm), where laminar flow dominates, as well as for converging glottis. For the uniform glottis with larger openings and for the diverging glottis, the pressure on the lower edge is negative. The pressure distribution on the vocal fold surfaces causes the characteristic movement of the mucous membrane which is important for the energy transfer between the airflow and the vocal folds, necessary for maintaining vocal fold vibrations. The fact that the forces are in phase with the movement, indicates that the vocal folds are mainly resistive at the fundamental frequency. The pressure on the upper part of the folds plays a less important role in the mechanism of vibration. This pressure is small in magnitude and it seems as if the main energy transfer from the airflow to the vibrating folds takes place in the inferior section of the glottis and that the superior section is driven mainly by mechanical coupling.

The entry loss coefficient has been found to be quite dependent on both glottal shape and volume flow. For the uniform glottis, this coefficient increases as the glottis widens. For the typical glottal widths of between 0.4 mm and 1.4 mm, it varies from 1.3 to 1.5 for a Reynolds number larger than 1000. In this high range of Reynolds number the coefficient is practically constant for each glottal opening. At a low Reynolds number, the entry loss coefficient rises rapidly as Re decreases. In phonation, Re would lie between 200 and 800 giving values of the coefficient between 1.8 to 1.4. For the non-uniform glottis, the loss coefficient is generally higher for a diverging glottis compared to other shapes of the same entry dimension.

The exit recovery coefficient depends also on the geometry of the glottal opening. Its value varies between 0.05 and 0.17 for the glottal dimensions tested. These values match the theoretical results derived from energy and momentum equations applied at exit. The generally accepted figure of 0.5, given by van den Berg, is too high and thus underestimates the total pressure drop across the laryngeal airway.

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