Entrance loss coefficients and exit coefficients for a physical model of the glottis with convergent angles

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Pressure distributions were obtained for 5°, 10°, and 20° convergent angles with a static physical model (M5) of the glottis. Measurements were made for minimal glottal diameters from $d = 0.005$ – 0.32 cm with a range of transglottal pressures of interest for phonation. Entrance loss coefficients were calculated at the glottal entrance for each minimal diameter and transglottal pressure to measure how far the flows in this region deviate from Bernoulli flow. Exit coefficients were also calculated to determine the presence and magnitude of pressure recovery near the glottal exit. The entrance loss coefficients for the three convergent angles vary from values near 2.3–3.4 for $d = 0.005$ cm to values near 0.6 for $d = 0.32$ cm. These coefficients extend the tables of entrance loss and exit coefficients obtained for the uniform glottis according to Fulcher, Scherer, and Powell [J. Acoust. Soc. Am. **129**, 1548–1553 (2011)]. © 2014 Acoustical Society of America. [<http://dx.doi.org/10.1121/1.4887477>]

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I. INTRODUCTION

Specifying the total transglottal pressure as the sum of pressure drops from the trachea to the entrance of the glottis, through the glottis, and from the exit of the glottis to a downstream location was a hallmark of the classic 1957 study by van den Berg *et al.*¹ The pressure drop from the trachea to the entrance of the glottis may be expressed with a Bernoulli-like equation modified with an entrance loss coefficient k_{ent} , namely,

$$P_6 = P_0 - \frac{k_{ent}\rho U_g^2}{2A_6^2}, \quad (1)$$

where P_6 and A_6 denote the pressure and the glottal area at tap 6, the location of the glottal entrance, $\rho = 0.00121$ g/cm³ is the density of air at room temperature, and U_g is the glottal flow rate. The quantity P_0 represents the upstream pressure in the trachea. The paper of van den Berg *et al.*¹ listed a value of 1.375 to describe the average of the entrance loss coefficients over the range of glottal diameters and transglottal pressures they examined for their rectangular glottis. This value was adopted in pioneering work on the two-mass model by Ishizaka and Matsudaira² and by Ishizaka and Flanagan.³

Because of its importance in describing the relationship between the pressure at the glottal entrance and the glottal flow rate, a number of studies were done with different

physical models of the glottis^{4–11} to examine the distribution of pressures along the inferior glottal surface, within the glottis, and at the glottal exit and beyond. The model with the greatest sampling of pressure locations has been the physical model M5 (Refs. 9–11) for which an extensive set of pressure distributions have been measured. Pressure distributions were taken for glottal diameters (sometimes referred to as the glottal width) of $d = 0.005, 0.01, 0.02, 0.04, 0.08, 0.16$, and 0.32 cm, convergent angles of 5°, 10°, 20°, and 40°, divergent angles of 5°, 10°, 20°, and 40°, and the uniform glottis (0°). For each angle and diameter, from three to five transglottal pressures of interest for phonation were used. Recent work by Fulcher, Scherer, and Powell¹² that focused on the 35 pressure distributions taken for the uniform glottis showed that the entrance loss coefficients ranged in size from 17.6 at $d = 0.005$ cm to 0.7 at $d = 0.32$ cm. This large variation would be responsible for major differences in the magnitude of the glottal flow rate for a given drop between the subglottal pressure and the pressure at the glottal entrance. Conversely, if the glottal flow rate is given, a large entrance loss coefficient would give a large difference of pressures in the subglottal region and within the glottis from that expected, for example, with the Bernoulli equation. Of course, such large pressure differences would result in large differences in the aerodynamic forces driving the vocal folds.^{2,3,13–28}

van den Berg *et al.*¹ also made an estimate of the exit coefficient (0.5) to account for the effects of pressure recovery near the glottal exit. Ishizaka, Matsudaira, and Flanagan^{2,3} did not adopt this value but used Newton's second law to derive a formula for the exit coefficient the

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values of which are considerably smaller than the value estimated by van den Berg *et al.* Fulcher *et al.*¹² did not find that the exit coefficients calculated from the M5 data agreed with the trend of behavior of the exit coefficients as predicted by the Newton's law derivation (possibly due to the different glottal exit geometry). This trend requires the exit coefficients to become larger as the glottal diameter increases in contrast to the behavior of the coefficients calculated from the M5 pressure distributions.

The reasons for the current interest in a careful examination of the properties of entrance loss coefficients and exit coefficients^{12,29} may be traced to two experimental papers by Titze, Schmidt, and Titze³⁰ in 1995 and by Chan, Titze, and Titze³¹ in 1997 and a follow-up paper by Chan and Titze³² in 2006. These papers describe a series of experiments with physical models of the vocal fold mucosa undertaken to measure phonation threshold pressures (PTP) expressly for the purpose of examining predictions made by the surface wave model (SWM) Titze¹³ developed in his 1988 paper. Some of the predictions of the SWM were supported by the experiments, but the experiments uncovered two important discrepancies. One of these is that the SWM predicts that the threshold pressure of the uniform glottis should approach zero as the glottal half-width becomes very small provided that the entrance loss coefficients and the exit coefficients remain approximately constant. None of the 1995 and 2006 experiments exhibit this behavior. In Ref. 29, Fulcher and Scherer showed that the M5 pressure distributions were not consistent with the notion of approximately constant values for the entrance loss coefficient when the glottal width was very small. Rather the calculations showed that the dependence of the entrance loss coefficient on glottal width was close to that of an inverse linear relationship. Moreover, such a relationship removes the discrepancy between the 1995 and 2006 experiments and the predictions²⁹ of the SWM.

Another discrepancy arose in observations of the prephonatory angle dependence of the PTP observed in the 1997 experiments of Chan *et al.*³¹ The SWM model predicted that for approximately constant entrance loss coefficients and exit coefficients (such as one might obtain from the average of van den Berg *et al.* or from the formula derived from Newton's second law by Ishizaka and his colleagues), the PTPs for divergent glottal angles should be lower than those measured for convergent glottal angles or for the uniform glottis. The 1997 experiments found that for a given glottal diameter, the PTP for most divergent angles was considerably larger than that for the uniform glottis and comparable to the PTP for convergent angles.

This second discrepancy is one of the motivations for the calculations presented in this paper. Does the resolution of this discrepancy also depend upon the behavior of the entrance loss coefficients, in this case their angle dependence for a given glottal diameter and transglottal pressure? The purpose of the present paper is to report calculations of the entrance loss and exit coefficients for typical convergent angles expected during the glottal cycle,^{33–40} with the eventual aim of discovering whether the variations of these coefficients with angle are large enough to play a significant role

in resolving the discrepancy between the predictions of the SWM and the PTP measurements of the 1997 paper. Divergent angles will be considered in a future publication. One reason for separating the convergent and divergent cases is that certain additional complications attend the question of flow separation in the divergent case, and thus one would expect the convergent case to be simpler.

The dependence of the entrance loss coefficients for the uniform glottis on Reynolds number for the eight glottal diameters considered in Ref. 12 is shown in Fig. 1. The Reynolds numbers there were calculated from the formula $Re = V D_h / \nu$, where V is the average velocity of the air within the glottis, D_h is the hydraulic diameter^{9,41,42} (four times the glottal area at the minimal diameter divided by the glottal perimeter), and $\nu = 0.151 \text{ cm}^2/\text{s}$ is the kinematic viscosity of air. With a few exceptions, the entrance loss coefficients for a given diameter decrease monotonically as the Reynolds number increases. There is considerable overlap for glottal diameters sharing the same Reynolds number, a feature worth further exploration at some future time.

A two-dimensional schematic diagram of the glottal channel for the 5° (included angle) convergent case is shown in Fig. 2. There the locations of the 16 pressure taps in M5 used to measure the distribution of pressures along the inferior glottal surface, within the glottis, and past the glottal exit are shown. The break in the line between taps 15 and 16 indicates that the distance between these two taps is larger than one might infer from the diagram. The glottal entrance is located at tap 6, and thus the first 5 taps are in the subglottal region. The first tap on the superior glottal surface is tap 13. Taps 13 and 14 lie within the glottal exit plane. The minimal glottal diameter d is defined at tap 11, where the two medial surfaces are nearest each other. A three-dimensional perspective of the vocal fold inserts and the wind tunnel is given in Fig. 1 of Ref. 12. There one sees that 14 of the pressure taps are located on one of the vocal fold inserts. Tap 15 is located in what would be the lateral ventricle wall if the false vocal folds were present, and 16 is located downstream beyond the arytenoid cartilages (if they were present). Tap 0 (not shown) is located upstream inferior to the vocal folds in the tracheal wall. The curvature radii at the glottal entrance and the glottal exit were carefully designed to approximate those of the normal male larynx (Fig. 1 of Ref. 9).

FIG. 1. (Color online) Dependence of the entrance loss coefficients on Reynolds number for the uniform glottis at eight glottal diameters.

FIG. 2. (Color online) Schematic diagram of the 5° convergent channel of model M5. The 5° angle is the included angle measured between the two glottal walls. Because the walls are mirror images of each other, the channel is symmetric. Locations of the pressure taps are shown. The glottal entrance is located at an axial distance of 0.211 cm (tap 6) and the glottal exit at 0.511 cm (tap 13). The minimal glottal diameter d occurs at tap 11.

II. PRESSURE DISTRIBUTIONS

Representative pressure distributions for the 5° convergent glottal angle are shown in Fig. 3. Each data point presented there is an average of four pressure readings. A

FIG. 3. (Color online) Pressure distributions within and near the 5° converging glottis for minimal diameters of (A) 0.01 cm and (B) 0.08 cm. For the former case, the transglottal pressures range from 3 to 25 cm H₂O, and for the latter case, the range of transglottal pressures is from 3 to 15 cm H₂O. For the larger diameter, the NFW pressure distributions were taken on the side from which the flow jet had separated, and the FW distributions were taken on the side to which the jet adhered. Reynolds numbers are included in parentheses for each pressure distribution.

consideration of the standard deviations of the pressure readings suggests that one should assign an error bar of 1% or 2% to each data point. A 2% error bar is comparable to the circles used to denote the observed pressures in Fig. 3 for the smaller transglottal pressures, and it is slightly larger than the circles used to denote the observed pressures for the larger transglottal pressures there. For each distribution, the pressure drop between the tracheal pressure and the pressure tap increases as the channel narrows between taps 1 and 6 (as the pressure decreases between these points along the inferior vocal fold surface). For the two cases shown in Fig. 3, the pressure drop continues to increase monotonically between taps 6 and 11, where the channel reaches its narrowest point. Beyond tap 11, the channel widens for a short distance near the glottal exit, and thus the pressure drop decreases in most cases (as the pressure increases) between tap 11 and the glottal exit at tap 13 for most glottal diameters. The behavior of the pressure in this region is a local pressure recovery. For a given transglottal pressure, the pressure change between taps 6 and 11 for the smaller diameter (0.01 cm) is considerably larger than that for the larger diameter (0.08 cm), consistent with the expectation of a larger viscous effect for the narrower channel.

The glottal expansion between taps 11 and 13 produces a short diverging extension of the converging glottal walls (taps 6–11); this encourages the formation of a flow jet that separates from one of the channel walls, skewing toward the opposite wall. For the 5° converging angle, this effect occurs for the larger pressures at glottal diameters of 0.02 and 0.04 cm and most pressures at the larger diameters. The side to which the jet adheres is called the flow wall (FW), and the opposite side is called the nonflow wall (NFW). Pressures along the flow wall after the jet is detached tend to be lower than those on the nonflow wall. The cross channel pressure difference tends to increase as the glottal diameter increases and as the transglottal pressure increases. The largest value of this difference in Fig. 3(B) is 6.1% of the transglottal pressure, which occurs at tap 15 for the 15 cm H₂O transglottal pressure case, and the difference becomes as large as about 11.7% for the $d=0.32$ cm case (not shown). Observable pressure differences between the flow wall and the nonflow wall for the 5° convergent case tend to move upstream as the glottal diameter increases.

Pressures on the two sides of the glottis were obtained with the following method. Human hairs were attached to a small rod and put into the upstream section of the wind tunnel near the top of the channel. These hairs were long enough so that they followed the flow into the glottis and inclined toward the side to which the flow was headed, and they did not seem to disturb the flow. Thus one could distinguish the FW from the NFW by observing the ends of the hairs. To switch the flow to the opposite side, a paper guide approximately the height of the channel was used. Once the flow was switched, it was stable, and the paper guide could be removed. Thus one could observe pressures on the FW and the NFW with the same experimental setup. The stability of the location of the flow jet on either side of a symmetric channel was also observed in the earlier experiments by Durst, Melling, and Whitelaw.⁴³ They compared the cross-channel velocity profiles of the flow jets on either side of their channels and found

them to be almost mirror images of each other (Fig. 13 in Ref. 43). They were also able to switch the jet on one side to the other side using an appropriate lateral perturbation (in their case a small tube with a strong puff of air).

Two pressure distributions for the 10° convergent case are shown in Fig. 4. The $d = 0.01$ cm case is chosen to show that it is similar to the $d = 0.01$ cm case for the 5° convergent angle of Fig. 3(A), although one can recognize small differences near the glottal exit. The five curves in Fig. 4(A) are closer together near the glottal entrance than their counterparts in Fig. 3(A), but their shapes are similar. The $d = 0.32$ cm case has two local minima, a feature it shares with the 5° and 20° convergent pressure distributions (not shown) at this glottal diameter. One of the minima is near the glottal entrance, and one is near tap 11, where the glottal channel has its narrowest point. These minima occur for both the flow wall and the nonflow wall distributions. The minimum near the glottal entrance is also seen for the 5° convergent angle at $d = 0.16$ cm, but it is not clearly shown for the 10° convergent and the 20° convergent angles at this diameter. The differences between the flow wall and the nonflow wall pressures at $d = 0.32$ cm tend to be larger than those for any other diameter. This difference is 12.6% of the transglottal pressure at tap 11 for the 15 cm H₂O case of Fig. 4(B).

III. ENTRANCE LOSS COEFFICIENTS

Entrance loss coefficients provide a nondimensional quantitative measure of how the flow from the “trachea” to

the glottal entrance differs from lossless Bernoulli flow. To calculate this coefficient, it is convenient to write Eq. (1) in the form

$$k_{ent} = 2A_6^2 \frac{P_0 - P_6}{\rho U_g^2}. \quad (2)$$

The area A_6 is the area at the glottal entrance. It is the product of the glottal length l_g (1.2 cm in model M5) and the distance across the glottal channel at tap 6. Figure 2 clearly shows that this cross channel distance at tap 6 is not the same as the minimal glottal diameter (the cross channel distance at tap 11). To determine the cross channel distance at tap 6, one must add an increment to the minimal diameter. This increment is equal to twice the difference between the transverse distance coordinates of taps 11 and 6, and the numerical values of this increment are 0.0178, 0.0360, and 0.0734 cm for the 5°, 10°, and 20° convergent angles, respectively.

Equation (2) states that one requires the volume velocities or flow rates as well as the glottal areas and pressure drops to determine the entrance loss coefficients. These flow rates were measured for each minimal diameter and transglottal pressure for the 5°, 10°, and 20° convergent angles, and they are listed in the odd rows of Tables I–III. For the diameters of 0.04 cm and smaller, the flow rates tend to increase with increasing angle, and a comparison with Table I of Ref. 12 reveals that all of these flow rates are larger than the corresponding flow rates for the uniform case. (For an overview of the behavior of the flow rates for convergent angles, divergent angles, and the uniform case, see Fig. 4 of Ref. 44.) The flow rates tend to be almost the same for the larger diameters in the three tables for a given minimal diameter and transglottal pressure.

For the five largest diameters in each of the tables, the pressures on the flow wall side were different from those on the nonflow wall side. The experiments were performed so that the flow rates were the same when the pressures on the

FIG. 4. (Color online) Pressure distributions within and near the 10° convergent glottis for minimal diameters of (A) 0.01 cm and (B) 0.32 cm. Reynolds numbers are also included for each pressure distribution.

TABLE I. Flow rates (in cm³/s, odd rows) and entrance loss coefficients (dimensionless, even rows) for the 5° convergent glottis using model M5. Coefficients within 10% of 1.375 are given in boldface.

Pressure (cm H ₂ O)	1	3	5	10	15	25
Diameter (cm)						
0.005 (Flow rate)		4.00	6.69	12.58	17.29	25.23
(k_{ent})		2.210	2.322	1.717	1.542	1.342
0.01		15.17	21.42	33.58	42.98	58.33
		1.810	1.579	1.468	1.352	1.300
0.02		35.69	49.39	72.97	93.49	
		1.758	1.582	1.485	1.358	
0.04		84.85	111.1	163.9	206.4	
		1.387	1.339	1.247	1.186	
0.08		203.5	262.8	378.3	469.5	
		1.036	1.055	1.008	0.989	
0.16		420.3	553.3	826.0	1055	
		1.059	1.028	0.915	0.834	
0.32		577.4	1089	1514		
		0.869	0.740	0.642		

TABLE II. Flow rates (in cm³/s, odd rows) and entrance loss coefficients (dimensionless, even rows) for the 10° convergent glottis using model M5. Coefficients within 10% of 1.375 are given in boldface.

Pressure (cm H ₂ O) Diameter (cm)	1	3	5	10	15	25
0.005 (Flow rate)		4.80	7.79	13.99	18.68	26.44
(<i>k_{ent}</i>)		3.385	1.829	1.435	1.533	1.344
0.01		17.21	23.92	36.47	46.23	62.28
		1.717	1.478	1.424	1.372	1.274
0.02		39.67	52.70	79.66	99.30	
		1.585	1.549	1.371	1.332	
0.04		87.06	113.6	166.8	208.7	
		1.458	1.391	1.289	1.245	
0.08		206.7	265.7	382.0	471.9	
		1.037	1.057	1.017	1.003	
0.16		423.7	556.8	826.8	1058	
		1.062	1.012	0.909	0.836	
0.32	580.5	1098	1532			
	0.849	0.731	0.621			

flow wall side were measured as when the pressures on the nonflow wall side were measured. In most cases, there were no differences in the pressures at the glottal entrance as one might infer from Fig. 3(B). In those cases where the downstream flow separation was felt at the glottal entrance, the difference in pressures on the opposing walls was small in comparison with the difference near the glottal exit, as one might infer from Fig. 4(B). For example, the difference in the flow wall and the nonflow wall pressures near the glottal entrance in Fig. 4(B) is never more than 3.6%, less than 1/3 of the largest difference near the glottal exit. For the 5° convergent case of Table I, the largest difference at the glottal entrance is 2.6%, and for Table III the largest difference is about 1.1%. Because any possible differences between the flow wall and the nonflow wall pressures near tap 6 are small, the decision was made to average the flow wall and

TABLE III. Flow rates (in cm³/s, odd rows) and entrance loss coefficients (dimensionless, even rows) for the 20° convergent glottis using model M5. Coefficients within 10% of 1.375 are given in boldface.

Pressure (cm H ₂ O) Diameter (cm)	1	3	5	10	15	25
0.005 (Flow rate)		5.69	8.88	15.18	19.97	27.90
(<i>k_{ent}</i>)		2.884	0.527	1.256	1.320	1.093
0.01		19.21	26.04	39.12	49.07	65.57
		1.121	1.226	1.123	1.336	1.229
0.02		41.61	58.15	84.61	108.0	
		1.991	1.437	1.507	1.238	
0.04		92.27	120.2	175.9	219.8	
		1.306	1.278	1.190	1.129	
0.08		211.4	272.6	388.4	481.0	
		0.986	1.016	0.988	0.943	
0.16		424.7	557.6	824.4	1051	
		1.019	0.984	0.866	0.803	
0.32	590.7	1109	1536			
	0.763	0.661	0.569			

the nonflow wall pressures at this tap before calculating the entrance loss coefficients in Tables I–III.

The largest values of the entrance loss coefficients in the tables occur at the smallest minimal diameter. These values are 2.3 in Table I, 3.4 in Table II, and 2.9 in Table III. These values at the smallest diameter of the three tables in this paper are considerably smaller than those (as large as 17.6) for the uniform case in Table I of Ref. 12. The values in Tables I–III tend to decrease as the diameter increases and as the pressure increases, which follows the trends seen in the entrance loss coefficients for the uniform glottis. Most of the smallest values in Tables I–III are found at the diameter $d = 0.32$ cm with an exception in the first row of Table III, where one value is unusually small. The boldface entries indicate the coefficients in the tables that are within 10% of 1.375, the average value that van den Berg *et al.*¹ used to summarize their measurements of entrance loss effects. There are 9 such entries in Table I, 12 such entries in Table II, and 8 such entries in Table III. Thus one would expect 1.375 to be a reasonable estimate of entrance loss effects for several of the pressures at diameters from 0.005 to 0.04 cm, but this is a relatively small part of the range of glottal widths and pressures expected in typical phonation.

The dependence of the entrance loss coefficients on Reynolds number is shown in Fig. 5 for the three convergent angles of Tables I–III, where the coefficients tend to decrease as the Reynolds number increases, although there are quite a few exceptions to this behavior. This trend is in accord with the trend of Fig. 1 for the uniform glottis. However, one does not see as much overlap at different minimal diameters in Fig. 5 as in Fig. 1. Part of the reason for this is the difference of scale, but there are differences that cannot be accounted for in this manner. For example, if the coefficients of Fig. 5(A) are examined on the same scale as that of Fig. 1, the overlap of the 0.01 cm and the 0.02 cm cases is not as good as in Fig. 1, and the overlap of the 0.04 and the 0.08 cm cases is also not as good. The trends of the curves in Figs. 5(A) and 5(B) are easier to characterize than those in Fig. 5(C) because the latter figure includes more cases where the minimum values do not occur at the largest values of the Reynolds number.

IV. EXIT COEFFICIENTS

The exit coefficient is defined by comparing the pressure downstream at tap 16 with that at tap 11, where the glottal channel starts to expand near the glottal exit, viz.,

$$k_{ex} = 2A_{11}^2 \frac{P_{16} - P_{11}}{\rho U_g^2}. \quad (3)$$

In Eq. (3) A_{11} is the area of the glottal channel at tap 11, and P_{11} is the pressure at this tap. The glottal area is equal to the product of the glottal length l_g and the cross channel distance at tap 11. For all of the convergent angles, this cross channel distance is the minimal glottal diameter as can be inferred from Fig. 2. The definition of Eq. (3) requires that the exit coefficient be positive whenever the pressure at tap 16 is higher than that at tap 11 in anticipation that the shape of the

FIG. 5. (Color online) Dependence of the entrance loss coefficients on Reynolds number (A) for the 5° convergent angle, (B) the 10° convergent angle, and (C) the 20° convergent angle.

channel near the glottal exit will promote pressure recovery in most cases.

The exit coefficients for the three convergent angles are listed in Tables IV–VI. The flow rates listed in odd rows of Tables I–III were required to calculate the exit coefficients. Most of the exit coefficients for $d = 0.005$ cm and one of the entries for $d = 0.01$ cm are negative. Negative exit coefficients were also present in Table II of Ref. 12, which considered the uniform glottis. The negative sign is a signal that the pressures at tap 11 in these instances are higher than those for tap 16, indicating that the usual expectations about pressure recovery do not pertain for these cases. The negative sign may be connected with the size of the viscous effects in such narrow channels. At diameters of 0.02 cm and larger, the behavior of the exit coefficients is easier to

TABLE IV. Exit coefficients for the 5° convergent glottis.

Pressure (cm H ₂ O)	1	3	5	10	15	25
Diameter (cm)						
0.005		−2.924	−1.346	−0.465	−0.274	−0.149
0.01		−0.0003	0.0426	0.0671	0.0804	0.0855
0.02		0.1887	0.1556	0.1365	0.1053	
0.04		0.1272	0.0944	0.0803	0.0649	
0.08		0.0614	0.0604	0.0488	0.0417	
0.16		0.0548	0.0536	0.0305	0.0230	
0.32	0.0531	0.0339	0.0262			

characterize. They tend to become smaller as the transglottal pressure increases and as the minimal diameter increases.

Although the differences between the flow wall and the nonflow wall at tap 11 are larger than those at tap 6, they are still relatively small in comparison to the transglottal pressure. In the discussions of Figs. 3 and 4, it was stated that the largest differences between the flow wall and the nonflow wall pressures were about 12% and that these differences occurred at $d = 0.32$ cm. There is a slightly larger value of about 14% for the 20° convergent case, again at $d = 0.32$ cm. For $d = 0.16$ cm, the largest difference is 8.1% of the transglottal pressure for the 5° convergent case, 8.7% for the 10° convergent case, and 9.2% for the 20° convergent case. When differences occur at smaller diameters, they are smaller. Because these differences are not too large, it was also decided to average the pressures at tap 11 before computing the exit coefficients. In most cases, one would expect a calculation of the exit coefficient for the flow wall to be somewhat larger than the coefficients listed in the Tables IV–VI, and a calculation of the exit coefficient for the nonflow wall to be somewhat smaller than that listed in Tables IV–VI.

In Sec. IV of their classic work, where they dealt with the pressure distribution along the glottis, Ishizaka and Flanagan³ used Newton’s second law to examine the momentum changes for a sudden expansion of the glottal channel near the glottal exit. About the same time, the monograph by Ishizaka and Matsudaira² presented the same result. From these considerations, they derived a simple formula for the exit coefficient, namely,

$$k_{ex,IMF} = 2(1 - A_{11}/A_{vt})A_{11}/A_{vt}, \quad (4)$$

TABLE V. Exit coefficients for the 10° convergent glottis.

Pressure (cm H ₂ O)	1	3	5	10	15	25
Diameter (cm)						
0.005		−1.562	−0.5385	−0.0202	0.0501	0.0989
0.01		0.1269	0.1597	0.1471	0.1509	0.1551
0.02		0.2034	0.1854	0.1712	0.1558	
0.04		0.1284	0.1367	0.1018	0.0957	
0.08		0.0780	0.0802	0.0755	0.0732	
0.16		0.0805	0.0775	0.0612	0.0556	
0.32	0.0940	0.0817	0.0624			

TABLE VI. Exit coefficients for the 20° convergent glottis.

Pressure (cm H ₂ O)	1	3	5	10	15	25
Diameter (cm)						
0.005		-1.102	-0.386	-0.0928	0.0152	0.0127
0.01		0.0218	0.0459	0.0504	0.0605	0.0578
0.02		0.1863	0.1379	0.1313	0.1132	
0.04		0.1493	0.1283	0.1189	0.1074	
0.08		0.0985	0.1089	0.0818	0.0820	
0.16		0.1065	0.1020	0.0688	0.0616	
0.32	0.0853	0.0663	0.0525

FIG. 6. (Color online) Dependence of the exit coefficients on minimal glottal diameter for transglottal pressures of 3, 5, 10, and 15 cm H₂O at the (A) 5° convergent angle, (B) the 10° convergent angle, and (C) the 20° convergent angle. The calculated coefficients are compared with the formula derived by Ishizaka, Matsudaira, and Flanagan (IMF).

where the quantity A_{vt} denotes the area of the vocal tract (2.4 cm² for M5). It is noteworthy that this formula does not allow for any dependence of the exit coefficient on the transglottal pressure in contrast to the behavior of the exit coefficients listed in Tables IV–VI. The exit coefficients for the three convergent angles are plotted in Fig. 6 as functions of the minimal glottal diameter for transglottal pressures of 3, 5, 10, and 15 cm H₂O, where there are a sufficient number of entries in the tables to establish trends. For each of the angles, the coefficients reach a maximum near $d = 0.02$ cm and decrease between 0.02 and 0.08 cm. In some cases, there is a tendency to level off at larger diameters. The exit coefficients calculated from the M5 pressure distributions are not consistent with the Ishizaka-Matsudaira-Flanagan (IMF) result of Eq. (4). In particular, this formula requires an increasing trend with increasing minimal diameter, as shown by the dashed curves of Fig. 6, in contrast to the behavior of the curves obtained from the M5 data. The same kind of discrepancy was observed for the exit coefficients of the rectangular glottis.¹²

V. SUMMARY AND CONCLUSIONS

Entrance loss and exit coefficients were calculated from pressure distributions measured with the static physical model M5 for the converging angles of 5°, 10°, and 20°. The entrance loss coefficients exhibit trends similar to those of the rectangular glottis presented in an earlier publication,¹² namely, they tend to decrease with increasing glottal diameter and transglottal pressure. These trends are apparent in Tables I–III as well in Fig. 5, where the dependence of the entrance loss coefficients on Reynolds number is shown. None of the parts of Fig. 5 for the convergent angles possesses the same degree of overlap at different glottal diameters as the entrance loss coefficients in Fig. 1 for the uniform glottis. The entrance loss coefficients at small minimal diameters for all the convergent angles are considerably smaller than those for the uniform glottis.¹²

In certain cases, the exit coefficients are negative, indicating that pressure recovery does not occur. In Fig. 6, the dependence of the exit coefficients on minimal diameter was plotted for each of the convergent angles at transglottal pressures of 3, 5, 10, and 15 cm H₂O. None of the curves there showed the increasing trend with increasing glottal diameter expected from the formula derived by Ishizaka, Matsudaira, and Flanagan.^{2,3}

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