Experimental and computational study of intraglottal pressures in a three-dimensional model with a non-rectangular glottal shape

Saeed Torkaman

The University of Toledo
A Dissertation

entitled

Experimental and Computational Study of Intraglottal Pressures in a
Three-Dimensional Model with a Non-Rectangular Glottal Shape

by

Saeed Torkaman

Submitted to the Graduate Faculty as partial fulfillment of the requirements
for the Doctor of Philosophy Degree in Engineering

Dr. Abdollah A. Afjeh, Committee Chair

Dr. Ronald C. Scherer, Committee Co-Chair

Dr. Terry Ng, Committee Member

Dr. Ray Hixon, Committee Member

Dr. Cyril Masiulaniec, Committee Member

Dr. Patricia Komuniecki, Dean
College of Graduate Studies

The University of Toledo
May 2011
An Abstract of

Experimental and Computational Study of Intraglottal Pressures in a Three-Dimensional Model with a Non-Rectangular Glottal Shape

by

Saeed Torkaman

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Doctor of Philosophy Degree in Engineering

The University of Toledo
May 2011

The focus of this research was to experimentally and computationally study air pressures and air flows through a model of the human larynx. The model, M6, was a symmetric, three-dimensional physical model. In this model, the transverse plane of the glottis was formed by half-sinusoidal arcs for each medial vocal fold surface, creating a maximum glottal width at the midcoronal section.

To study the effects of different glottal shapes, three glottal angles were used, namely, 10° convergent, 0° uniform, and 10° divergent, with the single diameter of 0.16 cm. In addition, to capture the effects of changing glottal diameters, three diameters of 0.16, 0.04, and 0.01 cm in the midcoronal plane were used, all with the single angle of 0° (i.e., the uniform glottis). Inasmuch as the uniform case with maximum diameter (0.16 cm) was the common case in both groups, a total of five distinct pairs of modeled vocal folds were used.

Each case incorporated three rows of 14 pressure taps, located in the inferior-superior direction on the vocal fold surface at locations of the anterior (1/4), middle (1/2), and posterior (3/4) of the anterior-posterior span. This approach (i.e., empirically acquiring air pressure distributions at the three locations) has not been applied in prior studies. For each configuration, transglottal pressures of 0.294, 0.491, 0.981, 1.472, 1.962, and 2.453 kPa (i.e., 3, 5, 10, 15, 20, and 25 cm H$_2$O) were used.
To consider the effects of the presence of the arytenoid cartilages on the intraglottal pressures, a simplified model of the cartilages was fabricated as a single structure based on available physiological data, and the intraglottal pressures were measured with and without its presence. With the arytenoid cartilages structure in place, the glottis is an eccentric orifice. The empirical pressures were compared to computational results obtained with the CFD software package FLUENT. Also, flow visualization using a laser sheet and seeded airflow was applied to study the flow patterns exiting the glottis. The false vocal folds were not included in this study.

The glottis with half-sinusoidal arcs makes a difference relative to intraglottal pressures at the anterior (1/4), middle, and posterior (3/4) planes for all cases. The amount of the pressure difference across the three locations varied based on the glottal angle and diameter; however, the maximum pressure differences did not rise above approximately 8% of the transglottal pressure, even in the presence of the arytenoid cartilages. There were pressure and velocity gradients in both the axial (upstream-downstream) and longitudinal (anterior-posterior) directions, with primary gradients axially and secondary gradients longitudinally. The flow in the M6 model was more stable than in the M5 model downstream of the vocal folds and it did not skew except for the smallest glottal diameter; however, in the M5 model, even for large glottal diameters, the flow skews randomly and creates two different pressure distributions. Flow contraction toward the midcoronal plane within and downstream of the glottis was a primary finding of this study, which was not seen in the rectangular models of the glottis. The arytenoid cartilages structure produced additional secondary flow only for the cases with the largest glottal diameter, which changed the intraglottal pressures along the longitudinal direction.

The results of this study present initial information about the relationship among intraglottal pressures, flow patterns, and the three-dimensionality of the glottis. This study suggests that the pressures and flows within the glottis are three-dimensional,
and flow contraction in the sagittal plane is to be expected and considered in future phonatory modeling. Non-rectangular laryngeal geometries need to be accurately specified and are required in research programs of basic laryngeal function to establish benchmark empirical data.
To my supportive parents

and

my lovely wife, Nasim
Acknowledgments

I would like to thank my Ph.D. advisor, Dr. Abdollah A. Afjeh, who has given me the opportunity and direction to show my motivations and pursue my graduate study in mechanical engineering. His generosity and leadership opened a new window in my life and his endless support, in spite of his busy schedule, encouraged me during the hardships of research. This study would not have been possible without his provision.

I also wish to appreciate Dr. Ronald C. Scherer for the guidance and support he dedicated to me during this research. He is full of energy and new ideas. Although he is one the best in the phonation field, he never withheld from me his enormous knowledge. His enthusiasm in research trained me that perseverance and precision are two main columns of a prominent research.

I would also like to thank Dr. Bogdan Radu Kucinschi for all of his support and supervision during the experimental and computational processes of this study. He certainly is one of the key persons who helped me to proceed with this dissertation.

I would like to express my gratitude to the following individuals who contributed to the success of this research by accepting to be a member of my dissertation defense committee: Dr. Terry Ng, Dr. Ray Hixon, and Dr. Cyril Masiulaniec.

I would also like to thank Mr. John Jaegly and other machine shop crews for their efforts and support in manufacturing of the experimental device.

This dissertation was supported by grant number DC03577 from the National Institute of Health, Dr. Ronald C. Scherer (PI).
Contents

Abstract

Acknowledgments

Contents

List of Tables

List of Figures

1 Introduction

1.1 Physiology of the Larynx

1.2 Literature Review

2 Methodology and Approach

2.1 Experimental Method

2.1.1 Objectives

2.1.2 Experimental model

2.1.2.1 General view of the apparatus

2.1.2.2 Vocal fold geometry

2.1.2.3 Pressure measurement

2.1.2.4 Flow visualization

2.2 Computational Method
3 Results: Pressure Distributions and Volume Flow

3.1 Introduction

3.2 Variable Glottal Angles
   3.2.1 Without arytenoid structure
      3.2.1.1 Results
      3.2.1.2 Discussion
   3.2.2 With arytenoid structure
      3.2.2.1 Results
      3.2.2.2 Discussion

3.3 Variable Glottal Diameters
   3.3.1 Without arytenoid structure
      3.3.1.1 Results
      3.3.1.2 Discussion
   3.3.2 With arytenoid structure
      3.3.2.1 Results
      3.3.2.2 Discussion

4 Results: Flow Visualizations

4.1 Introduction

4.2 Variable Glottal Angles
   4.2.1 Without arytenoid structure
      4.2.1.1 Coronal plane
      4.2.1.2 Sagittal plane
   4.2.2 With arytenoid structure
      4.2.2.1 Coronal plane
6.2 Pressures and Velocities ........................................... 177
   6.2.1 Reynolds number and laminarity .............................. 177
   6.2.2 Computational model justification ................................ 178
   6.2.3 Variable glottal angles: midsagittal velocities ............ 178
   6.2.4 Variable glottal diameters: midsagittal velocities ........ 180
   6.2.5 Intraglottal pressure distributions: 2D vs. 3D models ...... 182
   6.2.6 M6 pressure gradients within the glottis .................... 187
6.3 Flow Contraction .......................................................... 192
   6.3.1 Comparison between M5 and M6 .................................. 192
   6.3.2 Secondary flow in model M6 .................................... 193

7 Conclusions ......................................................... 199
   7.1 Half-sinusoidal-arcs Glottis ...................................... 201
      7.1.1 Pressure gradients ............................................. 201
      7.1.2 Flow fields ..................................................... 202
   7.2 Eccentricity ......................................................... 203
      7.2.1 Pressure gradients ............................................. 203
      7.2.2 Flow fields ..................................................... 204

References ............................................................. 206

A Dynamic Similitude .................................................. 212

B Pressure transducer calibration .................................... 215

C M6 Labview code ...................................................... 219
# List of Tables

2.1 Exit radii of the vocal folds based on different glottal angles (real-life values). .................. 20

2.2 Characteristics of the computational grids used for the FLUENT simulations for the cases without the arytenoid structure. ............... 33

2.3 Characteristics of the computational grids used for the FLUENT simulations for the cases with the arytenoid structure. .................. 35

3.1 Standard of line styles and symbols used for the three different rows in the experimental and numerical results. ....................... 39

3.2 Acronyms for the five different glottal configurations used in the figures. 39

3.3 M6 glottal flows (in cm$^3$/s, real life), without the arytenoid structure, for different values of the transglottal pressure, $\Delta p_T$: comparison between experimental data and computational results. The computational results are presented for three grids (see Table 2.2): coarse (C), medium (M), and fine (F). ....................... 46

3.4 M6 glottal flows (in cm$^3$/s, real life), with the arytenoid structure, for different values of transglottal pressure, $\Delta p_T$: comparison between experimental data and computational results. The computational results are presented for three grids (see Table 2.3): coarse (C), medium (M), and fine (F). 60
3.5 M6 glottal flows (in cm$^3$/sec, real-life), without the arytenoid structure, for different values of transglottal pressure, $\Delta p$: comparison between experimental data and computational results. The computational results are presented for three grids (see Table 2.2): coarse (C), medium (M), and fine (F).

3.6 M6 glottal flows (in cm$^3$/sec, real-life), with the arytenoid structure, for different values of transglottal pressure, $\Delta p$: comparison between experimental data and computational results. The computational results are presented for three grids (see Table 2.3): coarse (C), medium (M), and fine (F).

4.1 Specifications of the flow visualizations for the cases with different glottal angles without the arytenoid structure for a transglottal pressure of 0.491 kPa (5 cm H$_2$O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

4.2 Specifications of the flow visualizations for the cases with different glottal angles without the arytenoid structure for a transglottal pressure of 1.472 kPa (15 cm H$_2$O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

4.3 Specifications of the flow visualizations for the cases with different glottal angles with the arytenoid structure for a transglottal pressure of 0.491 kPa (5 cm H$_2$O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

4.4 Specifications of the flow visualizations for the cases with different glottal angles with the arytenoid structure for a transglottal pressure of 1.472 kPa (15 cm H$_2$O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).
4.5 Specifications of the flow visualizations for the cases with different glottal diameters without the arytenoid structure for a transglottal pressure of 0.491 kPa (5 cm H₂O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

4.6 Specifications of the flow visualizations for the cases with different glottal diameters without the arytenoid structure for a transglottal pressure of 1.472 kPa (15 cm H₂O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

4.7 Specifications of the flow visualizations for the cases with different glottal diameters with the arytenoid structure for a transglottal pressure of 0.491 kPa (5 cm H₂O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

4.8 Specifications of the flow visualizations for the cases with different glottal diameters with the arytenoid structure for a transglottal pressure of 1.472 kPa (15 cm H₂O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

6.1 Computational axial velocities in m/s (real life) at the middle, anterior (1/4), and posterior (3/4) sections for the three glottal shapes without the arytenoid structure at the minimal glottal locations, for two values of the transglottal pressure, Δp_T,1=0.294 kPa, and Δp_T,2=2.453 kPa. The M6 computational results correspond to the finest grid in Table 2.2.

6.2 Computational axial velocities in m/s (real life) at the middle, anterior (1/4), and posterior (3/4) sections for the three glottal shapes with the arytenoid structure at the minimal glottal locations, for two values of the transglottal pressure, Δp_T,1=0.294 kPa, and Δp_T,2=2.453 kPa. The M6 computational results correspond to the finest grid in Table 2.2.
6.3 Computational axial velocities in m/s (real life) at the middle, anterior (1/4), and posterior (3/4) sections for the three glottal diameters without the arytenoid structure at the glottal exit (tap #11), for two values of the transglottal pressure, $\Delta p_{T,1} = 0.294$ kPa (3 cm H$_2$O), and $\Delta p_{T,2} = 2.453$ kPa (25 cm H$_2$O). The M6 computational results correspond to the finest grid in Table 2.2.

6.4 Computational axial velocities in m/s (real life) at the middle, anterior (1/4), and posterior (3/4) sections for the three glottal diameters with the arytenoid structure at the glottal exit (tap #11), for two values of the transglottal pressure, $\Delta p_{T,1} = 0.294$ kPa (3 cm H$_2$O), and $\Delta p_{T,2} = 2.453$ kPa (25 cm H$_2$O). The M6 computational results correspond to the finest grid in Table 2.2.

6.5 Comparison between the calculated M6 flow rates (in cm$^3$/s, real life), and flow rates calculated in the two-dimensional geometries corresponding to the anterior and middle planes in M6, for different values of transglottal pressure, $\Delta p_T$. The M6 computational results correspond to the finest grid in Table 2.2.
List of Figures

1-1 Views of the vocal folds: (a) Inhalation stroboscopic view, (b) Phonation stroboscopic view, (c) Inhalation schematic view, and (d) Phonation schematic view. ........................... 4

1-2 Larynx views: (a) Relative location of different laryngeal components in sagittal view, (b) Laryngeal components shown in frontal view, and (c) Laryngeal components shown in transverse view. .............. 6

1-3 Different shapes of glottis during a phonation cycle (Scherer [35]): (a) Glottal volume flow for one cycle, (b) Frontal view of the vocal folds for one cycle of vibration [after Hirano]. ...................... 7

1-4 (a) Schematic of the Plexiglas model M5 [37] seen in top view. All measures are actual model dimensions in cm. (b) Isometric view of M5. The rectangular diameter of the glottis can be seen. .............. 12

2-1 Schematic views of the M6 model: (a) isometric view, (b) top view (all model dimensions in cm). ................................. 16

2-2 Two different isometric views of the arytenoid structure attached to the vocal folds. ................................. 17

2-3 General view of the M6 apparatus. ................................. 17

2-4 View of test section of flow tunnel. The vocal folds and the arytenoid cartilages structure can be observed. ................................. 18
2-5 Design parameters and equations for the vocal fold pieces in coronal view [37] .................................................................................................................. 20

2-6 Views of the vocal fold pairs showing the anterior (1/4) ends on the left and isometric views on the right: (a) convergent, (b) uniform, and (c) divergent configurations of the glottis. ................................................................. 21

2-7 Different uniform vocal fold pairs showing the sagittal views: (a) maximum diameter (0.16 cm), (b) medium diameter (0.04 cm), and (c) minimum diameter (0.01 cm) configurations of the glottis. ...................... 23

2-8 Pressure taps on the vocal folds. There are three rows of taps on the vocal fold surface (Anterior, Middle and Posterior), each row containing 14 taps. Tap #6 is located at the entrance to the glottis, tap #12 is on the mid-region of the rounded surface of the glottal exit, while taps #13 and #14 are on the top surface of the vocal fold. .............. 25

2-9 Internal structure of the model vocal folds: (a) Upper section of the vocal folds through the middle tap row. (b) Middle section of the vocal folds in the middle row. (c) Internal passageways, secondary cylindrical voids, and tap pressures. ................................................................. 26

2-10 Electrical circuit of the M6 device. Air is driven through the system by a vacuum pump. The pressure transducers (PT0, PT1) are connected to the signal conditioners (SC) and data acquisition system (DAQ). The rotameter, shut off valve, and vacuum pump are also shown. . . . 28

2-11 Isometric view of the M6 model with visualization set up . . . . . 30

2-12 Camera position for flow visualization of the M6 model: a) Sagittal view, b) Coronal view ............................................................... 30

2-13 Three-dimensional structured mesh of the computational glottal model for the cases without the arytenoid structure (one quarter of the low-resolution mesh is shown). ........................................................... 34
2-14 Three-dimensional structured mesh of the computational glottal model flow field (airway) for the cases with the arytenoid structure (one half of the low-resolution mesh is shown).

3-1 Experimental and numerical pressure distributions for the convergent 10° case (C16) without the arytenoid structure at the three sections for \( \Delta p_T = 0.294 \) kPa (3 cm H\(_2\)O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-2 Experimental and numerical pressure distributions for the divergent 10° case (D16) without the arytenoid structure at the three sections for \( \Delta p_T = 0.294 \) kPa (3 cm H\(_2\)O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-3 Experimental and numerical pressure distributions for the uniform 0° case (U16) without the arytenoid structure at the three sections for \( \Delta p_T = 0.294 \) kPa (3 cm H\(_2\)O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-4 Experimental and numerical pressure distributions for the three glottal angles without the arytenoid structure at the three sections for \( \Delta p_T = 0.294 \) kPa (3 cm H\(_2\)O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-5 Experimental and numerical pressure distributions for the three glottal angles without the arytenoid structure at the three sections for \( \Delta p_T = 0.491 \) kPa (5 cm H\(_2\)O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-6 Experimental and numerical pressure distributions for the three glottal angles without the arytenoid structure at the three sections for \( \Delta p_T = 0.981 \) kPa (10 cm H\(_2\)O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
3-7 Experimental and numerical pressure distributions for the three glottal angles without the arytenoid structure at the three sections for $\Delta p_T = 1.472 \text{ kPa} \ (15 \text{ cm H}_2\text{O})$. Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-8 Experimental and numerical pressure distributions for the three glottal angles without the arytenoid structure at the three sections for $\Delta p_T = 1.962 \text{ kPa} \ (20 \text{ cm H}_2\text{O})$. Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-9 Experimental and numerical pressure distributions for the three glottal angles without the arytenoid structure at the three sections for $\Delta p_T = 2.453 \text{ kPa} \ (25 \text{ cm H}_2\text{O})$. Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-10 Experimental and numerical pressure distributions for the convergent $10^\circ$ case (C16) with the arytenoid structure at the three sections for $\Delta p_T = 0.294 \text{ kPa} \ (3 \text{ cm H}_2\text{O})$. Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-11 Experimental and numerical pressure distributions for the divergent $10^\circ$ case (D16) with the arytenoid structure at the three sections for $\Delta p_T = 0.294 \text{ kPa} \ (3 \text{ cm H}_2\text{O})$. Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-12 Experimental and numerical pressure distributions for the uniform $0^\circ$ case (U16) with the arytenoid structure at the three sections for $\Delta p_T = 0.294 \text{ kPa} \ (3 \text{ cm H}_2\text{O})$. Note that the ANT and POS pressures were nearly identical and thus closely overlap.
3-13 Experimental and numerical pressure distributions for the three glottal angles with the arytenoid structure at the three sections for $\Delta p_T = 0.294$ kPa (3 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap. ................... 61

3-14 Experimental and numerical pressure distributions for the three glottal angles with the arytenoid structure at the three sections for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap. ................... 62

3-15 Experimental and numerical pressure distributions for the three glottal angles with the arytenoid structure at the three sections for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap. ................... 63

3-16 Experimental and numerical pressure distributions for the three glottal angles with the arytenoid structure at the three sections for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap. ................... 64

3-17 Experimental and numerical pressure distributions for the three glottal angles with the arytenoid structure at the three sections for $\Delta p_T = 1.962$ kPa (20 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap. ................... 65

3-18 Experimental and numerical pressure distributions for the three glottal angles with the arytenoid structure at the three sections for $\Delta p_T = 2.453$ kPa (25 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap. ................... 66
3-19 Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), without the arytenoid structure at the three sections for $\Delta p_T = 0.294$ kPa (3 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap. ......................................................... 69

3-20 Experimental (symbols) vs. computational (lines) comparison for Flow-Wall (FW) and Non-Flow-Wall (NFW) for the diameters of 0.01 cm (real life) for case (U01), glottal angle of 0° (uniform), for transglottal pressures 0.294 kPa (3 cm H$_2$O). The presented numerical results correspond to the finest mesh in Table 2.2. .............................. 71

3-21 Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), without the arytenoid structure at the three sections for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap. ......................................................... 74

3-22 Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), without the arytenoid structure at the three sections for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap. ......................................................... 75

3-23 Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), without the arytenoid structure at the three sections for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap. ......................................................... 76
3-24 Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), without the arytenoid structure at the three sections for $\Delta p_T = 1.962$ kPa (20 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-25 Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), without the arytenoid structure at the three sections for $\Delta p_T = 2.453$ kPa (25 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-26 Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), with the arytenoid structure at the three sections for $\Delta p_T = 0.294$ kPa (3 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-27 Experimental (symbols) vs. computational (lines) comparison for Flow-Wall (FW) and Non-Flow-Wall (NFW) for the diameters of 0.01 cm (real life for case (U01), glottal angle of 0° (uniform), for transglottal pressures 0.294 kPa (3 cm H$_2$O). The presented numerical results correspond to the finest mesh in Table 2.3.

3-28 Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), with the arytenoid structure at the three sections for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-29 Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), with the arytenoid structure at the three sections for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
3-30 Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), with the arytenoid structure at the three sections for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-31 Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), with the arytenoid structure at the three sections for $\Delta p_T = 1.962$ kPa (20 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-32 Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), with the arytenoid structure at the three sections for $\Delta p_T = 2.453$ kPa (25 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.

3-33 Experimental and computational flow resistances for all models with and without the arytenoid structure.

4-1 Schematic view of the parameters which defined in the glottal flow visualizations: a) Isometric view of the vocal folds, b) Coronal view (laminar core length defined as L1), and c) Sagittal view (laminar core length and contraction parameters defined as L2, W1, W2, A1, and A2, respectively).

4-2 Glottal flow visualization for the convergent case (C16), without the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.

4-3 Glottal flow visualization for the uniform case (diameter of 0.16 cm, U16), without the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.
4-4 Glottal flow visualization for the divergent case (D16), without the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal. ................. 99

4-5 Glottal flow visualization for the convergent case (C16), without the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal. ................. 100

4-6 Glottal flow visualization for the uniform case (diameter of 0.16 cm, U16), without the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal. .... 101

4-7 Glottal flow visualization for the divergent case (D16), without the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal. ................. 102

4-8 Glottal flow visualization for the convergent case (C16), with the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal. 107

4-9 Glottal flow visualization for the uniform case (diameter of 0.16 cm, U16), with the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal. ......................... 108

4-10 Glottal flow visualization for the divergent case (D16), with the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal. 109
4-11 Glottal flow visualization for the convergent case (C16), with the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal.

4-12 Glottal flow visualization for the uniform case (diameter of 0.16 cm, U16), with the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal.

4-13 Glottal flow visualization for the divergent case (D16), with the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal.

4-14 Glottal flow visualization for the uniform case (diameter of 0.04 cm, U04), without the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.

4-15 Glottal flow visualization for the uniform case (diameter of 0.01 cm, U01), without the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.

4-16 Glottal flow visualization for the uniform case (diameter of 0.04 cm, U04), without the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.

4-17 Glottal flow visualization for the uniform case (diameter of 0.01 cm, U01), without the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.
4-18 Glottal flow visualization for the uniform case (diameter of 0.04 cm, U04), with the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O):
a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal. ................................................................. 123

4-19 Glottal flow visualization for the uniform case (diameter of 0.01 cm, U01), with the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O):
a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal. ................................................................. 124

4-20 Glottal flow visualization for the uniform case (diameter of 0.04 cm, U04), with the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O):
a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal. ................................................................. 125

4-21 Glottal flow visualization for the uniform case (diameter of 0.01 cm, U01), with the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O):
a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal. ................................................................. 126

5-1 Schematic view of mesh in mid-coronal plane for the M6 model for the uniform glottis. Section A-A indicates the mid-sagittal plane out of the page. ................................................................. 129

5-2 Pressure contours at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for convergent glottis (C16): a) Anterior (1/4)-coronal, and b) Middle-coronal. Values of the contours are in kPa. ................................................................. 131

5-3 Coronal velocity profiles within the glottis at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for convergent glottis (C16): a) Anterior (1/4)-coronal, and b) Middle-coronal. ................................................................. 132
5-4 Pressure contours at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.16 cm (U16): a) Anterior (1/4)-coronal, and b) Middle-coronal. Values of the contours are in kPa.  

5-5 Coronal velocity profiles within the glottis at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.16 cm (U16): a) Anterior (1/4)-coronal, and b) Middle-coronal.  

5-6 Pressure contours at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for divergent glottis (D16): a) Anterior (1/4)-coronal, and b) Middle-coronal. Values of the contours are in kPa.  

5-7 Coronal velocity profiles within the glottis at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for divergent glottis (D16): a) Anterior (1/4)-coronal, and b) Middle-coronal.  

5-8 Flow streamlines in the mid-sagittal plane, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), with different glottal angles: a) convergent (C16), b) uniform glottis (U16), and c) divergent (D16). D=0.16 cm.  

5-9 Pressure contours at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for convergent glottis (C16): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. Values of the contours are in kPa.
5-10 Coronal velocity profiles within the glottis at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for convergent glottis (C16): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. ........................................ 142

5-11 Pressure contours at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.16 cm (U16): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. Values of the contours are in kPa. ... 144

5-12 Coronal velocity profiles within the glottis at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.16 cm (U16): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. ........................................ 145

5-13 Pressure contours at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for divergent glottis (D16): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. Values of the contours are in kPa. ........................................ 147

5-14 Coronal velocity profiles within the glottis at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for divergent glottis (D16): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. ........................................ 148

5-15 Flow streamlines in the mid-sagittal plane, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), with different glottal angles: a) convergent (C16), b) uniform glottis (U16), and c) divergent (D16). D=0.16 cm. ........................................ 150
5-16 Flow streamlines in the mid-sagittal plane, focused on glottis, with the arytenoid structure, for \( \Delta p_T = 0.981 \text{ kPa} \) (10 cm H\(_2\)O), with different glottal angles: a) convergent (C16), b) uniform glottis (U16), and c) divergent (D16). \( D=0.16 \text{ cm} \). ........................................... 151

5-17 Sagittal velocity profiles within the glottis for convergent glottis (C16) for \( \Delta p_T = 0.981 \text{ kPa} \) (10 cm H\(_2\)O), for two configurations: a) without the arytenoid structure, and b) with the arytenoid structure. ........ 153

5-18 Sagittal velocity profiles within the glottis for uniform glottis with diameter of 0.16 cm (U16) for \( \Delta p_T = 0.981 \text{ kPa} \) (10 cm H\(_2\)O), for two configurations: a) without the arytenoid structure, and b) with the arytenoid structure. .................. 154

5-19 Sagittal velocity profiles within the glottis for divergent glottis (D16) for \( \Delta p_T = 0.981 \text{ kPa} \) (10 cm H\(_2\)O), for two configurations: a) without the arytenoid structure, and b) with the arytenoid structure. ........ 155

5-20 Pressure contours at different coronal planes, without the arytenoid structure, for \( \Delta p_T = 0.981 \text{ kPa} \) (10 cm H\(_2\)O), for uniform glottis with diameter of 0.04 cm (U04): a) Anterior (1/4)-coronal, and b) Middle-coronal. Values of the contours are in kPa. .................... 158

5-21 Coronal velocity profiles within the glottis at different coronal planes, without the arytenoid structure, for \( \Delta p_T = 0.981 \text{ kPa} \) (10 cm H\(_2\)O), for uniform glottis with diameter of 0.04 cm (U04): a) Anterior (1/4)-coronal, and b) Middle-coronal. .................... 159
5-22 Pressure contours at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.01 cm (U01): a) Anterior (1/4)-coronal, and b) Middle-coronal. Values of the contours are in kPa. Small pressure gradient (0-0.2 Pa) was imposed as a boundary condition across the duct downstream of the glottis. ................................................................. 161

5-23 Coronal velocity profiles within the glottis at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.01 cm (U01): a) Anterior (1/4)-coronal, and b) Middle-coronal. Small pressure gradient (0-0.2 Pa) was imposed as a boundary condition across the duct downstream of the glottis. ................................................................. 162

5-24 Flow streamlines in the mid-sagittal plane, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), with different glottal diameters: a) diameter of 0.01 cm (U01), b) diameter of 0.04 cm (U04), and c) diameter of 0.16 cm (U16). ................................................................. 164

5-25 Pressure contours at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.04 cm (U04): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. Values of the contours are in kPa. . . . . . . . . 166

5-26 Coronal velocity profiles within the glottis at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.04 cm (U04): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. . . . . . . . . 167
5-27 Pressure contours at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.01 cm (U01): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. Values of the contours are in kPa. Small pressure gradient (0-0.2 Pa) was imposed as a boundary condition across the duct downstream of the glottis.

5-28 Coronal velocity profiles within the glottis at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.01 cm (U01): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. Small pressure gradient (0-0.2 Pa) was imposed as a boundary condition across the duct downstream of the glottis.

5-29 Flow streamlines in the mid-sagittal plane, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), with different glottal diameters: a) diameter of 0.01 cm (U01), b) diameter of 0.04 cm (U04), and c) diameter of 0.16 cm (U16).

5-30 Flow streamlines in the mid-sagittal plane, focused on glottis, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), with different glottal diameters: a) diameter of 0.01 cm (U01), b) diameter of 0.04 cm (U04), and c) diameter of 0.16 cm (U16).

5-31 Sagittal velocity profiles within the glottis for uniform glottis with diameter of 0.04 cm (U04) for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for two configurations: a) without the arytenoid structure, and b) with the arytenoid structure.
5-32 Sagittal velocity profiles within the glottis for uniform glottis with diameter of 0.01 cm (U01) for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for two configurations: a) without the arytenoid structure, and b) with the arytenoid structure.

6-1 Comparison between the pressure distributions in M6 (mid-coronal and anterior (1/4) coronal plane) with the pressure distributions in similar two-dimensional geometries, for a transglottal pressure of 0.981 kPa (10 cm H$_2$O). The M6 mid-coronal results are represented with a continuous line, and M6 anterior (1/4) plane with a dashed line. The two-dimensional pressures are represented with dash-dot line (−·) for the mid-coronal, and dash-dot-dot (−··) line for the anterior (1/4) plane. The uniform distributions (“U16”) are identified by the symbol (○), and the divergent ones (“D16”) by (△). No symbol is used for the convergent distributions (“C16”).

6-2 Axial velocity profiles in midcoronal and anterior (1/4) planes at glottal entrance (tap #6 position, x=0) and near exit (tap #11 position) (symbol ◦) for the convergent case. Comparison between M6 and the corresponding two-dimensional cases, for a transglottal pressure of 0.981 kPa (10 cm H$_2$O). The M6 mid-plane results are represented by a continuous line, and the M6 anterior (1/4) plane by a dashed line (−−). The two-dimensional pressures are represented with dash-dot line (−·) for the mid-plane, and dash-dot-dot (−··) line for the anterior (1/4) plane. The lines with symbols are for the near-exit velocity profiles.
6-3 Pressure Gradients in the Anterior-Posterior Direction in the Glottis.
“+” means pressure is higher than at mid, “-” lower than at mid, and 0 same as at mid. A circle around the symbol indicates a difference of at least 4% of $\Delta p_T$ from the middle. A dashed circle means the Anterior-Posterior gradient is more than 7% of $\Delta p_T$.

6-4 Results of FLUENT simulations in the mid-sagittal section (transglottal pressure 0.981 kPa or 10 cm H$_2$O). The first row depicts the mid-coronal section (for reference). The middle row shows the total pressure contours and also streamlines. The last row shows contours of z-velocity (i.e., velocity in the anterior-posterior direction). The red and blue color levels correspond to +8 and -8m/s, respectively. Column (a): M5 model (uniform rectangular geometry, glottal diameter of 0.16 cm); Column (b): M6 model (uniform sinusoidal glottis, glottal diameter of 0.16 cm).

6-5 Anterior to posterior velocity profiles in the midsagittal plane of the M6 10° convergent glottis, at three axial locations: $x = 0$ cm (i.e., glottal entrance), 0.1 cm and 0.2 cm. The transglottal pressure is 0.981 kPa (10 cm H$_2$O).

6-6 Velocity profiles in a transverse section located at the glottal exit ($x=0.3$ cm), for a transglottal pressure of 0.981 kPa (10 cm H$_2$O), for all three geometries: 10° convergent, 0° uniform, and 10° divergent. The dotted lines trace the projected minimal glottal perimeter.

B-1 The calibration setup of the pressure transducers

B-2 Pressure-Voltage graph of PT0 (Flow meter)

B-3 Pressure-Voltage graph of PT1 (Pressure meter)

C-1 The M6 Labview code
Chapter 1

Introduction

Effective verbal communication in any society and with any language requires adequate voice and articulation. Relative to voice and speech production, accurate and effective diagnostics and rehabilitation, improvement of communication skills through training, and accurate predictive computer simulation require a comprehensive knowledge of voice and speech science. This research program supports these observations through its emphasis on empirical measurements of phonatory aerodynamics using a new, more realistic laryngeal model.

When the air from the lungs passes through the larynx during phonation, the shape of the glottis changes as the result of fluid-structure interaction with the vocal folds. The glottis shape varies in a cyclic manner, from convergent during opening to approximately uniform near maximum excursion, to a divergent shape during closing. The simultaneous variation of both the glottal shape and diameter leads to changes in the air pressure distributions on the vocal folds, and thus the driving surface forces that participate in creating vocal fold motion. Accurate measurement of these pressures and forces is important to understand basic notions of vocal fold vibration and produce accurate voicing acoustics.

Empirical pressure distributions using laryngeal models can be applied to multi-
mass analytic computer models, and can be used to test the pressure and flow accuracies of computational models in that the latter can embed such data either as empirical modifications of equations or as look-up tables. In addition, empirical data are critical for Navier-Stokes fluid flow solutions within phonation models because such empirical data can be used to verify computational accuracy.

Obtaining air pressures on the vocal fold surfaces of humans and excised animals is problematic due to the small size and high speed of motion of the vocal folds. Even dynamic models of phonation with slowly moving sides have limitations in this regard. Thus, static models with various laryngeal configurations have been used to obtain intraglottal pressures. The notion that permits the application of these pressures to dynamic computer models has been the sufficiency of the quasi-steady assumption of the physics within the glottal airway.

Physical models that have measured intraglottal pressures have typically had parallel vocal folds that form rectangular passages in the transverse plane of the glottis. Examples include the works of Wegel [47], van den Berg et al. [46], Ishizaka and Matsudaira [18], Gauffin et al. [15], Scherer et al. [39], Li et al. [26], and others. The use of models with rectangular glottal shapes (called two-dimensional models) assume that the primary driving forces do not appreciably alter in the anterior-posterior direction of the glottis at any anterior-posterior location along the glottis due to a relatively large length-width aspect ratio and assumed negligible end effects. The use of these two-dimensional models have provided valuable insights into the aerodynamic aspects of phonation as well as empirical information for computer models of phonation.

The shape of the dynamically moving glottis is not uniform in the anterior-posterior direction, however. The vocal folds are attached at the anterior end (anterior commissure) and during phonation can have a wide range of vocal process gap distances within the phonatory adductory range. The general shape of the vocal folds during phonation is more realistically modeled in the transverse plane as a
half-sinusoidal curve with the maximum width (or diameter) near the middle of the membranous glottis, during the maximum excursion and other phases of the phonatory cycle. Thus, the dynamic glottis is three dimensional, with changes in glottal shape anteriorly to posteriorly, as well as inferiorly to superiorly. It is this three dimensionality that is explored here.

The purpose of this study is to investigate the intraglottal pressures in a non-rectangular physical glottal model called M6. It is an extension of the two-dimensional M5 model [37, 38, 40]. Model M6 is used to determine whether or not the axial intraglottal air pressure distributions at different anterior-posterior locations differ when the glottis takes on the three-dimensional shape. The effects of the arytenoid cartilages is another concern of this research. If the results show that the three-dimensionality of the vocal folds and the presence of the arytenoid cartilages make significant differences, then realistic modeling needs to take these different pressure distributions into account.

The placement of the arytenoid cartilages posteriorly creates an eccentric configuration for the flow coming toward the glottis from the trachea, in that the airflow must “bend” around the undersurface toward the glottis. In this research program, when a simplified model of the arytenoid cartilages is not included, a slab of material that runs a distance inferiorly and superiorly in place of the arytenoid cartilages is used.

1.1 Physiology of the Larynx

The larynx is a cylindrical grouping of cartilage, muscles, and soft tissue which contains the vocal folds. Figure 1-1 shows the stroboscopic and schematic views of the vocal folds during inhalation and phonation situations. During inhalation, muscle contraction moves the cartilages of the larynx apart and the air passes by the folds,
Figure 1-1: Views of the vocal folds: (a) Inhalation stroboscopic view, (b) Phonation stroboscopic view, (c) Inhalation schematic view, and (d) Phonation schematic view.

http://www.ohsu.edu/ent/voice/images/normal.jpg
reaching the lungs without much flow resistance, but during phonation, the two vocal folds attached to the arytenoid cartilages of the larynx come toward each other and make a narrow gap. The vocal folds will then oscillate via aerodynamic pressures of the air passing through the glottis when the transglottal pressure is high enough.

The larynx is located at the top of the trachea and below the root of the tongue and the hyoid bone, as shown in Fig. 1-2. It is the essential sphincter guarding the entrance into the trachea and functions also as the organ of voice. The vocal folds (or vocal cords) are composed of a mucous membrane with an underlying thyroarytenoid muscle. The glottis takes different configurations: open during inhalation, closed when holding one’s breath, and vibrating for speech or singing.

During phonatory vibration, the shape of the glottis changes from convergent to uniform and then to divergent continuously (see Fig. 1-3). They vibrate like an oscillation valve, modulating the flow of air being expelled from the lungs, creating air pulses during phonation. The acoustic signal so produced is filtered by the vocal tract and radiated at the mouth as the output acoustic signal of speech. The power source for speech is the elevated pressure in the lungs and the resulting air flow through the glottis and trachea. The transglottal (or translaryngeal) pressure and geometry of the glottis (and nearby supraglottal structures) establish the intraglottal pressures of the glottis, which are associated with the lateral forces on the vocal folds. The vocal folds oscillate in response to these lateral forces according to their mechanical properties.

1.2 Literature Review

The voice production mechanism at first glance looks very simple, like a child’s whistle, but indeed, it is a combination of non-linear, time-dependent fluid mechanics and structural muscle interaction phenomena which make it difficult to study; it
Figure 1-2: Larynx views: (a) Relative location of different laryngeal components in sagittal view, (b) Laryngeal components shown in frontal view, and (c) Laryngeal components shown in transverse view.

http://wildiris3.securesites.net/cms_prod/files/course/182/EMTB4_fig1.jpg
Figure 1-3: Different shapes of glottis during a phonation cycle (Scherer [35]): (a) Glottal volume flow for one cycle, (b) Frontal view of the vocal folds for one cycle of vibration [after Hirano].
is complicated and involves multi-disciplinary research. Empirically obtained intra-glottal pressures using physical models of the larynx, together with theories from fluid mechanics, have historically provided the basic notions of phonatory aerodynamics, as well as the basic equations used in multi-mass models of phonation.

Laryngeal aerodynamics, a relatively new field, going back to only the early 1930’s, deals mainly with the flow physics occurring in the larynx during phonation. Classic equations have been offered by Wegel [47] who was one of the pioneers in this field. He made brass models of the larynx and measured the transglottal pressure drops for different flow rates to find a relationship between these two parameters for various geometries of the glottis. He offered an empirical derivation of the equations of aerodynamics in the larynx.

Afterward, van den Berg et al. [46] made a model of the larynx with a rectangular (parallel plate) glottis and measured the air resistance within that model. He followed the one-dimensional Bernoulli equation for the viscous flow inside the glottis and based on the experimental results, he introduced an empirical formula for loss factor as a function of the flow rate for different glottis diameters, which have been used often in later studies.

The first effort to make a realistic analytic computer model of the larynx was done by Flanagan and Landgraf [14]. They modeled the elastic and dynamic properties of the vocal folds as a single-mass and spring which resembled the self-oscillation concept of the vocal fold. Although this model was a good start, it could only produce a limited variety of oscillations. Since this model had just one mass, it could not show the phase difference along the vocal fold and therefore it could not reconstruct the different shapes of the glottis (i.e., convergent, uniform, and divergent) during phonation. To remedy the restrictions of the one-mass model, Ishizaka and Flanagan [17] introduced a two-mass model which comprised two oscillating masses representing the upper and lower parts of vocal folds. For the sake of simplicity and
symmetry, the other vocal fold was considered to be a mirror image of the first one.

The masses were coupled by a spring and were allowed to move laterally, and viscous resistance of the vocal fold tissues was modeled by two dampers. The results showed that the masses moved relative to each other with a 55 degree phase difference via a correct choice of the parameters. Their results for the open quotient was around 0.6 which matched the observations of human phonation. Although the two-mass model was an important step forward compared to prior studies, still it was far from the real and continuous model of the larynx. One of the methods to improve the multi-mass models was to increment the number of the masses. Titze [42, 43] studied a 16 mass-model and obtained better results for oscillation modes.

During phonation the vocal folds oscillate continuously, which means that every quantity related to phonation is time-dependent with both relatively steady and periodic components. Some significant experimental studies have been reported dealing with dynamic models and unsteady phenomena occurring in phonation. For instance, Pelorson et al. [31] studied theoretically and experimentally the flow inside static models of glottis. They mimicked the unsteady conditions by manipulating the air flow passing through the glottis by using an abrupt pressure variation. Zhang et al. [49] used a dynamic model of the vocal folds which was composed of a set of elastic vocal fold replicas such that one of them oscillated at a time. Deverge et al. [10] used the same concept but with rigid replicas. Recently, Kucinschi [21] developed an apparatus to study the flow through a dynamic mechanical model experimentally. The scaled-up model could mimic variation of both the glottal diameter and angle, and the motion of the model could be driven at different frequencies.

Since the study of pulsating jet flow is complicated, accurate measurement and calculation of glottal flow resistance, flow rate, and intraglottal pressures are almost impossible. The quasi-steady assumption of the physics within the glottal airway, as given by Ishizaka and Matsudaira [18], and Flanagan [13], and later supported by
Mongeau et al. [28], Zhang et al. [49, 48], and Kucinschi et al. [23], with limitations near glottal closure (Park and Mongeau [30]), has been extensively applied in phonation studies. Based on the quasi-steady assumption, static configurations can be used to replicate the oscillatory geometry of the vocal folds, and the instantaneous amount of each physical quantity can be assumed equivalent to its steady flow amount in a static system with the same geometry. This concept holds best for glottal diameters that are not small (i.e., near closure).

Static models have been widely used to get aerodynamic data inside the glottis such as the pressure distributions, and flow rates for different glottal geometries (Gauffin et al. [15], Scherer [34], Scherer et al. [39], and Scherer and Guo [36]), and were applied in this research too.

Computational modeling and analysis of physical phenomena have become increasingly common in recent years. Scientists and engineers have used computational tools to complement and/or replace experimental methods since validated computational methods provide a less expensive and more flexible tool to study physical phenomena. Guo and Scherer [16] used a finite-element method to obtain constant flow data computationally in an orifice resembling the larynx. A static physical model is mechanically and numerically simpler than a dynamic model, and simulation of complex shapes of the larynx in static configurations require less computational effort than simple dynamic shapes involving unsteady flows. Zhao [50] numerically studied the sound radiation from glottal subsonic jets for static and dynamic models. He compared the results of applying different numerical methods, like Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS), and proposed a quasi-one-dimensional model of the larynx.

Scherer et al. [37] studied intraglottal pressure distributions for a Plexiglas model of the larynx (M5) with a uniform glottis having symmetric and oblique configurations. The model had 14 pressure taps on the vocal fold surfaces and a rectangular
diameter of 0.04 cm (see Fig. 1-4). They acquired different pressure distributions on the two sides of glottis when the flow skewed to one side as it exited the glottis, and suggested that this phenomenon may contribute to normal jitter values and differences in vocal folds phasing. Scherer et al. [38] also used the same apparatus for different configurations of the vocal folds to check the effects of glottal angles on pressure distributions within the glottis. Shinwari et al. [40] demonstrated the flow pattern within and downstream of the glottis of the previous work by flow visualization techniques. They used a laser sheet and seeded airflow to indicate flow separation and downstream circulation. They showed that separation points did not change with flow rate in the symmetric glottis but for the oblique glottis moved upstream as flow rate increased. In all of these works, computational results complemented the empirical data by illuminating the flow behavior in different cases.

Alipour et al. [2] studied velocity profiles inside a Plexiglas model of the human larynx with a divergent glottis, a computational model, and an excised canine larynx. To measure the velocity profile downstream of the vocal folds, hot wire anemometry was used. They proposed a laminar flow with a parabolic velocity profile upstream of the glottis. They reported a turbulent flow regime downstream of the glottis and skewness of out-flow jet.

Reynolds numbers for the fluid flow within the glottis, as reported in many studies [37, 38, 40], have relatively low values (typically 100-10,000). Also, laminar schemes for computational solutions have resulted in excellent matches of pressures and flows. Flow visualization results suggest glottal flow is laminar until separation occurs (see Chapter 4). Due to the relatively low velocity magnitudes inside the larynx, the flow can generally be considered incompressible, justified by the small values of the flow Mach number ($Ma \leq 0.2$). Hence, the flow performance within the glottis will be investigated in this research by solving the three-dimensional, incompressible, and laminar form of the Navier-Stokes equations accompanied by the continuity equation.
Figure 1-4: (a) Schematic of the Plexiglas model M5 [37] seen in top view. All measures are actual model dimensions in cm. (b) Isometric view of M5. The rectangular diameter of the glottis can be seen.
The significance of three dimensionality of the vocal folds has been addressed in recent studies. Triep et al. [44, 45] used 3D dynamic models of the vocal folds in analyzing the unsteady vortex shedding downstream of the human glottis by means of high speed PIV measurements. Numerous studies using dynamic, static, and self-oscillating models of the vocal folds have been performed, e.g., Krane et al. [20], Erath et al. [12], Deverge et al. [10], and Li et al. [25]. These models consider a rectangular transverse section; that is, the frontal cross-section of the glottis at different locations in the anterior-posterior direction was constant. Becker et al. [6] used an inhomogeneous, self-oscillating synthetic model of the vocal folds to represent the fluid-structure-acoustic coupling. The results supported the existence of the Coanda effect during phonation, and the flow skewness to one fold and separation from the other. Drechsel et al. [11] investigated a symmetric two-layer, self-oscillating, life-size vocal fold model to show the influence of the vocal tract and false folds on the glottis jet. They found that the false folds interfere with the vortex shedding and changes the flow skewness direction.

A number of numerical simulations of the larynx were developed in the past to study various aspects of phonation, e.g., Bae et al. [5], Luo et al. [27], Tao and Jiang [41], and Larsson et al. [24]. Among all the studies reviewed above, almost none of them provided sufficiently detailed information about the flow field in real configurations of glottis. Most of the studies used over-simplified two- or three-dimensional models such that the complexity of the real glottis geometries was ignored. The current research (the studies reported in this dissertation) extends the prior studies by taking into consideration non-rectangular effects of the glottal geometry. To do this, a half-sinusoidal wall represented the vocal fold medial surface. To measure pressure values at more points, three rows of pressure taps were designed into the models. Also, the arytenoid cartilages, which were not considered in prior studies, were modeled and the effects on the glottis wall pressures were evaluated.
Chapter 2

Methodology and Approach

2.1 Experimental Method

2.1.1 Objectives

The purposes of this study are to determine the aerodynamics effects (i.e., axial intraglottal air pressure distributions at different anterior-posterior locations, flow rates, and flow patterns) for three different glottal angles and three glottal diameters due to applying the half-sinusoidal glottal curvature and the presence of the arytenoid cartilages structure. Therefore, the M6 model was built which included the vocal folds with non-rectangular glottal shape for three different glottal angles, namely convergent $10^\circ$, uniform $0^\circ$, and divergent $10^\circ$ and three glottal diameters ($0.16$, $0.04$, and $0.01$ cm real-life). Each vocal fold had three rows of 14 pressure taps located at the anterior ($1/4$), middle, and posterior ($3/4$) of the anterior-posterior span. The arytenoid cartilages structure was modeled and installed in the M6 model to investigate the eccentricity effects of the arytenoid structure on the aerodynamics of the airflow. Flow visualization was made for each case to depict the flow pattern of the airflow downstream of the glottis. The details of the M6 apparatus are presented in this chapter.
2.1.2 Experimental model

2.1.2.1 General view of the apparatus

Model M6 is an advancement of the M5 model [37, 38, 40] and is an enlarged physical model of the human larynx with a scaling factor of 7.5 (like M5). The enlargement permitted the establishment of an array of pressure taps close to each other so that relatively complete pressure distributions could be obtained. The enlargement by the factor of 7.5 also permitted highly accurate pressure and flow measurements within the model. Dynamic similitude concepts (see Appendix A) led to the model having pressures that were 56.25 times lower than real-life pressures, while the model flow rates were 7.5 times larger.

Figure 2-1 presents a general view of the M6 apparatus. It includes a tunnel made of clear Plexiglas with 25.4 mm (1 in) thick walls. The total length of the tunnel is 3.83 m (12.56 ft), of which the section downstream of the larynx is 2.8 m in order to minimize end effects that might disturb the flow patterns and glottal pressures. The Plexiglas side plates were machined at The University of Toledo using a CNC milling machine. In the first portion of this research (measuring the pressures without the arytenoid cartilages structure), the lower half of the tunnel height was occupied by a slab of high density foam, such that the rectangular cross-section of the tunnel was 90 mm high (corresponding to the anterior-posterior larynx dimension) and 126 mm wide, corresponding to a real life section of 1.2 cm × 1.68 cm. Next, a simplified model of the arytenoid cartilages (see Fig. 2-2) was placed adjacent to the vocal folds to study the effects of the airflow through the eccentric placement of the glottis. In order to ensure a uniform airflow upstream of the vocal folds (i.e., in the subglottal region), a honeycomb-type flow-straightening section was mounted at the tunnel entrance (Fig. 2-1).

A general view of the experimental setup is shown in Fig. 2-3. The vocal folds,
Figure 2-1: Schematic views of the M6 model: (a) isometric view, (b) top view (all model dimensions in cm).

the tubing manifold for the pressure taps from a vocal fold to the pressure scanner, the interface panel of the Labview program on the monitor, and other parts of the electric circuit can be observed. Figure 2-4 shows the test section of the flow tunnel. The dark structure is the arytenoid cartilages structure which has been modeled by Solidworks software and its G-code file was extracted for use by the CNC machine for the manufacturing process.
Figure 2-2: Two different isometric views of the arytenoid structure attached to the vocal folds.

Figure 2-3: General view of the M6 apparatus.
Figure 2-4: View of test section of flow tunnel. The vocal folds and the arytenoid cartilages structure can be observed.
2.1.2.2 Vocal fold geometry

The profiles of the M6 vocal folds in coronal (frontal) view were similar to those used in the M5 model [22]. Figure 2-5 illustrates design parameters and equations of the vocal fold pieces in coronal view [37]. The numerical values of $T$ (thickness of the average male larynx) and $R_o$ are represented in real life values. For the three glottal angles studied in this research, the entrance radius ($R_L$) was constant (=0.15 cm), but the exit radii ($R_\Psi$) differed as the glottal angle ($\Psi$) changed (see Table 2.1).

As Fig. 2-6 shows, the glottis model is symmetric, being formed by two identical model vocal folds that are mirror images of each other across the mid-sagittal plane, and in the transverse plane the profile of the medial surface of each vocal fold is half-sinusoidal. The half-sinusoidal shaping of the medial vocal folds, as well as of the motion of the vocal folds, appears to be a reasonable first approximation. Titze [9] and Rothenberg [33] used this profile for their modeling criteria. Relative to this curvature, the extreme anterior and posterior edges of the vocal folds are in contact, while the maximum distance (i.e., nominal glottal width) is located at the middle of the anterior-posterior span (midcoronal or mid-membranous). The glottal width is thus twice the lateral concavity (indentation) of each model vocal fold. The symmetrical sinusoidal profile is described by:

$$y_p(z) = I_G \sin(\pi z / L)$$

where $I_G$ (see Fig. 2-7) is the indentation of each fold, $L$ is the anterior-posterior distance (1.2 cm real life), and $z$ is the coordinate of the anterior-posterior direction ($0 \leq z \leq L$), with the origin at the posterior location.

As the vocal fold shape changes during the phonatory cycle (from convergent to uniform, and then to divergent), a large number of instantaneous frontal profiles can be considered for a static investigation. As Fig. 2-6 shows, three representative frontal
Figure 2-5: Design parameters and equations for the vocal fold pieces in coronal view [37]

Table 2.1: Exit radii of the vocal folds based on different glottal angles (real-life values).

<table>
<thead>
<tr>
<th>Glottal angles (Ψ)</th>
<th>Exit radii $R_\Psi$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convergent 10°</td>
<td>0.0908</td>
</tr>
<tr>
<td>Uniform 0°</td>
<td>0.0987</td>
</tr>
<tr>
<td>Divergent 10°</td>
<td>0.108</td>
</tr>
</tbody>
</table>
Figure 2-6: Views of the vocal fold pairs showing the anterior (1/4) ends on the left and isometric views on the right: (a) convergent, (b) uniform, and (c) divergent configurations of the glottis.
profiles, namely convergent 10°, uniform 0°, and divergent 10°, have been chosen for the first part of this research, with the maximum glottal width of 0.16 cm (real-life) at the midcoronal location of the smallest glottal transverse (projected) area. The 0.16 cm diameter is located near the glottal exit for the convergent case, at the glottal entrance for the divergent case, and from entrance to near exit for the uniform case. Figure 2-6 shows frontal end and isometric views of the vocal folds for the three conditions. During the phonatory cycle, the width (or diameter) of the vocal folds also changes. To study the effects of the different diameters on pressure distribution along the vocal folds, two additional diameters for the uniform case were tested in the second part of this research (see Fig. 2-7). To cover a reasonably wide range of indentations, additional medium and minimum glottal diameters of 0.04 cm and 0.01 cm (real-life), respectively, were considered (2IG in Fig. 2-7).

One of the model vocal folds of each pair had pressure taps that were used to measure intraglottal pressures on the wall of the vocal fold. The glottal wall pressures were measured using three rows of 14 pressure taps, located at three different coronal cross-sections, viz., the midsection and two sections symmetrically located 0.3 cm (real life) from the mid-section. The pressure taps, therefore, were at the anterior (1/4), middle (1/2), and posterior (3/4) distances along the vocal folds. The taps were numbered in the axial (primary flow) direction (Fig. 2-8) such that tap #6 corresponded to the glottal entrance. Taps #1-5 were on the inferior vocal fold surface, taps #6-11 along the straight portion of the vocal fold, tap #12 on the surface at the middle of the glottal exit expansion curvature, and taps #13 and #14 on the superior horizontal surface of the vocal fold adjacent to the glottal exit. Additional pressure taps were located on the right tunnel wall in the supra-glottal region (taps #0 and #15-19 in Fig. 2-1). The downstream tap (tap #0) was used to establish the desired transglottal pressure (imposed by adjusting the flow so that the pressure at tap #0 equaled the desired transglottal value). The rest of the additional
Figure 2-7: Different uniform vocal fold pairs showing the sagittal views: (a) maximum diameter (0.16 cm), (b) medium diameter (0.04 cm), and (c) minimum diameter (0.01 cm) configurations of the glottis.
taps helped to monitor the wall pressures immediately downstream of the vocal folds.

The vocal folds were designed using Solidworks (3D CAD design software) and were meshed using GAMBIT (meshing software package for CFD analysis). Due to the complexity of the active part (the vocal fold piece with pressure taps), each part was designed separately to deal with different constrains. Accommodating 42 isolated pressure taps and their passageways with no air leaks between the channels was complicated, but possible (see Fig. 2-9).

The vocal folds were fabricated according to Fig. 2-5 using rapid prototyping technology. The parts were generated layer-by-layer with fusible plastic material (ABS-M30). Flow resistance inside the passageways would be relatively high if the passageways were narrow. To reduce the flow resistance inside the passageways, the diameters of the passageways should be as large as possible. However, due to the size of the vocal folds, the available space within the model for all 42 pressure taps was limited. By increasing the diameters of the passageways, the distance between two adjacent passageways would decrease and the chance of flow leaks between them would increase. Therefore, an optimum method, a staggered design, was chosen (see Fig. 2-9a). In the staggered arrangement, half of the passageways (i.e., seven) were located in section A-A, situated 2 mm (model units) adjacent to the row of pressure taps (section B-B), while the other half were 2 mm on the other side, in section C-C. Also, there was a gradual increase in the internal diameter of the passageways from the pressure taps on the vocal fold surface to the manifold. The connection between the pressure taps and the passageways was made by means of secondary cylindrical voids (Fig. 2-9(b,c)). These voids were added based on the manufacturer recommendation to help the evacuation of axillary material during the fabrication of the vocal folds. The pressure taps were designed and built perpendicular to and flush with the glottal surface (Fig. 2-9). The glottal pressure taps were flat (no ridges) and had a diameter of 0.0762 cm (0.030 in) for the cases with the glottal diameter of
Figure 2-8: Pressure taps on the vocal folds. There are three rows of taps on the vocal fold surface (Anterior, Middle and Posterior), each row containing 14 taps. Tap #6 is located at the entrance to the glottis, tap #12 is on the mid-region of the rounded surface of the glottal exit, while taps #13 and #14 are on the top surface of the vocal fold.
Figure 2-9: Internal structure of the model vocal folds: (a) Upper section of the vocal folds through the middle tap row. (b) Middle section of the vocal folds in the middle row. (c) Internal passageways, secondary cylindrical voids, and tap pressures.
0.16 cm, corresponding to 0.0102 cm (real life), less than a tenth of the glottal gaps at each tap. For the cases with lower glottal diameters (0.04, and 0.01 cm), the tap diameters were 0.0254 cm (0.010 in), corresponding to 0.0034 cm (real life). Thus, the taps were not expected to alter or disturb the pressures or the flows within the glottis. The axial position of the pressure taps in all three rows was identical. All passageways led to the connection manifold. Stainless steel tubing press-fitted in the plastic manifold provided further connection to the pressure scanner panel through flexible silicon (TYGON) tubing.

2.1.2.3 Pressure measurement

Figure 2-10 shows a schematic of the M6 tubing and equipment connections. Air was drawn through the tunnel by generating a negative gauge pressure downstream using a vacuum pump. The pressure taps were connected to a computer-controlled pressure scanner (Scanivalve SSS-48C MK4) with a programmable switch and connection for each inlet port to a low-pressure transducer (PT1 in Fig. 2-10). A separate low-pressure transducer (PT0) of the same type (DP103, Validyne Engineering Sales Corp., Northridge, CA) was used to monitor the transglottal pressure. Both of the pressure transducers were calibrated by a micromanometer (Microtector, Dwyer Instruments, CAT No. 9/83) precisely (see Appendix B). Each transducer was connected to a signal conditioner (SC, model CD15, Validyne Engineering), which, in turn, was wired to a data acquisition card (DAQ, model NI USB-6221).

The conditioned signal from the transducers was delivered to the data acquisition card and sampled at a rate of 100 samples/sec. A LabView computer program was designed for data acquisition and processing (see Appendix C). A stabilization time of 60 sec was allowed for each pressure port. The actual acquisition time was 15 sec for each port, and the average value was reported as the measured pressure. Based on the manufacturer’s specifications, as well as on data replication, the uncertainty of
Figure 2-10: Electrical circuit of the M6 device. Air is driven through the system by a vacuum pump. The pressure transducers (PT0, PT1) are connected to the signal conditioners (SC) and data acquisition system (DAQ). The rotameter, shut off valve, and vacuum pump are also shown.

The pressure measurements was estimated to be approximately 5 Pa (real life) or less. The volumetric flow rate was measured by a rotameter (Fischer-Porter 10A1027) with a range of 20-1000 L/min. The transglottal pressure was indirectly adjusted by changing the flow rate. The flow rate measurement accuracy was approximately 6 cm$^3$/sec (real-life).

Recordings were made as follows. The flow rate was increased until the desired transglottal pressure was obtained at sensor PT0. The tap pressures were then automatically measured in Labview by scanning each of the pressure ports, starting with tap #1. The procedure required approximately 75 seconds for each tap. To maintain constant conditions during the experiment, the transglottal pressure was monitored
by frequently reading the PT0 signal to assure its consistency. Since the indicator element of the flow meter did not vibrate ("bobble") during measurements, the flow rate reported was the average of the values measured during the overall measurement time. Real life transglottal pressures of 0.294, 0.491, 0.981, 1.472, 1.962, and 2.453 kPa (i.e., 3, 5, 10, 15, 20, and 25 cm H$_2$O) were used.

### 2.1.2.4 Flow visualization

Figure 2-11 shows the experimental setup used to visualize the airflow through the M6 model. The setup included a 532 nm laser (Hercules Green Handheld Laser, Laserglow Co.), a smoke generator (F-650 Hurricane, smoke fluid substance: water base premium #FJP), and a digital photo/video camera (CASIO EX-F1). The camera is capable of acquiring images at a rate of 60 fps using a shutter speed of 1/40,000 s in photo mode, and 1,200 fps in video mode. The laser was equipped with a cylindrical lens that converted the beam output into a laser sheet necessary for visualization. The pressure taps on the surface of the vocal folds were covered by thin tape during visualization experiments to avoid clogging.

In order to investigate the effect of the half-sinusoidal shape in the transverse plane on the flow behavior, visualizations were made in both the coronal and sagittal planes. Figure 2-12 shows the position and orientation of the camera, laser, and vocal folds in these two planes. Figure 2-12(a,b) present the diagrams of the optical setup for sagittal and coronal visualizations, respectively. The laser axis was inclined 30° for the coronal views with reference to the tunnel axis to avoid requiring a downstream mirror inserted inside the tunnel (which could introduce flow perturbations).

To investigate the effects of the arytenoid structure on the flow regime in this study, the visualizations were made in two conditions: a) without the arytenoid structure, and b) with the arytenoid structure. Two specific pressures (0.294, and 1.472 kPa) were chosen for visualizations. The first representing pressures used in
Figure 2-11: Isometric view of the M6 model with visualization set up

Figure 2-12: Camera position for flow visualization of the M6 model: a) Sagittal view, b) Coronal view
soft phonation, the second for loud phonation. Eight photos for each case (2 views (sagittal and coronal), 2 pressures, and 2 conditions (with, without the arytenoid structure)) were obtained. For the five different cases (studied in this research), the total number of photos was forty.

2.2 Computational Method

2.2.1 Objectives

In this study, the empirical results are accompanied with the corresponding computational results. Computational results can provide both a consistency verification of the experimental data, as well as additional data that are beyond the scope of the empirical experiment (e.g., complete pressure and velocity fields). The details of the computational model are presented below.

2.2.2 Computational model

The governing equations of the flow (i.e., Navier-Stokes equations) were solved numerically by using the finite-volume CFD code FLUENT, which had been previously used for other experiments [37, 40, 23]. Based on the flow visualization studies and given the relatively small velocities associated with phonation (generally characterized by a low Mach number, $Ma < 0.2$), it was assumed for numerical simulation purposes that the glottal flow could be described as laminar and incompressible. This simplification was subsequently supported by the good agreement of the experimental and computational pressure curves (see Chapters 3 and 4). Numerical simulations were performed for transglottal pressures of 0.294, 0.491, 0.981, 1.472, 1.962, and 2.453 kPa (i.e., 3, 5, 10, 15, 20, and 25 cm H$_2$O). For the largest transglottal pressure, 2.453 kPa (25 cm H$_2$O), simulations performed with the ideal-gas compressible
flow model showed negligible differences when compared with the incompressible flow results.

The steady, implicit double-precision version of the pressure-based solver with SIMPLEC pressure-velocity coupling was chosen, as well as second order schemes for the momentum and pressure equations. Pressure boundary conditions were used. The desired transglottal pressures were imposed at the inlet, and zero gage pressure required at the outlet (except for the smallest diameter case, where a downstream pressure gradient from 0 to 0.2 Pa (real life) was imposed so as to generate the observed flow skewing). The simulations were considered converged when the mass and velocity residuals became less than $10^{-5}$.

A structured mesh topology of hexahedral cells was used for all cases. In the experimental setup the model vocal folds were in contact at both the anterior and posterior ends (see Fig. 2-6). The computational mesh became degenerate on the contact edges, with a negative impact on the accuracy of the simulations. In order to eliminate this problem, the vocal folds were separated by a very small gap (i.e., 0.03 mm) at the ends instead of coming to a very sharp corner of the computational model. The small size of the gap was expected to alter the computational results only to a negligible extent. Once the gap was included in the model, the anterior and posterior faces were meshed with two-dimensional (quadrilateral) structured cells. The meshing was performed such that cells close to the glottal walls were finer than those near the longitudinal axis, in order to better account for larger velocity gradients near and at the wall. The anterior-posterior glottal edges were subsequently discretized, and finally the three-dimensional mesh was generated. Although the larynx is geometrically symmetric, the entire glottal space was considered in the computations in order to capture possible asymmetries of the flow.

Figure 2-13 shows a typical mesh for a three-dimensional glottis (the uniform, 0.16 cm case, is represented) for the cases that the arytenoid cartilages were replaced
Table 2.2: Characteristics of the computational grids used for the FLUENT simulations for the cases without the arytenoid structure.

<table>
<thead>
<tr>
<th>Mesh type</th>
<th>Convergent 10° Cells</th>
<th>Nodes</th>
<th>Uniform Cells</th>
<th>Nodes</th>
<th>Divergent 10° Cells</th>
<th>Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>330,240</td>
<td>352,755</td>
<td>252,120</td>
<td>273,494</td>
<td>473,580</td>
<td>501,774</td>
</tr>
<tr>
<td>Medium</td>
<td>712,160</td>
<td>820,749</td>
<td>602,316</td>
<td>702,910</td>
<td>936,000</td>
<td>1,067,930</td>
</tr>
<tr>
<td>Fine</td>
<td>2,641,920</td>
<td>2,731,365</td>
<td>2,016,960</td>
<td>2,101,799</td>
<td>3,788,640</td>
<td>3,900,731</td>
</tr>
</tbody>
</table>

with the slab. Only one quarter of the mesh is shown to avoid a cluttered image. Since the anterior-posterior (i.e., slanted vertical direction in Fig. 2-13) velocity gradients were expected to be smaller than those in the lateral and axial directions, the mesh density in the anterior-posterior direction was generally lower.

Three types of grids were used in the simulations. The coarse grids contained between $2.5 \times 10^5$ and $4.75 \times 10^5$ cells. The medium mesh was derived from the coarse grid such that the first two layers of cells adjacent to the wall were refined (i.e., one cell was split into eight cells). A finer mesh was created by splitting all the cells in the coarse mesh. Table 2.2 presents the characteristics of each mesh for all cases (uniform, convergent, and divergent glottal shapes without the arytenoid structure).

For the cases with the arytenoid structure, the computational domain was more complicated than for the cases without the arytenoid structure. The flow domain had a triangle cavity in the section inferior to the arytenoid structure, and a sharp expansion at the exit of the glottis near the arytenoid region. Figure 2-14 shows only one-half of the mesh in order to make a comprehensible view. To capture the flow behavior in these cases (i.e., flow separation and flow streamlines), the flow domain was divided into several parts. For each part, the structured mesh was much denser than the cases without the arytenoid structure. This caused the number of the cells for each case to increase exponentially. Similar to the cases without the
Figure 2-13: Three-dimensional structured mesh of the computational glottal model for the cases without the arytenoid structure (one quarter of the low-resolution mesh is shown).
Table 2.3: Characteristics of the computational grids used for the FLUENT simulations for the cases with the arytenoid structure.

<table>
<thead>
<tr>
<th>Mesh type</th>
<th>Convergent 10° Cells</th>
<th>Convergent 10° Nodes</th>
<th>Uniform Cells</th>
<th>Uniform Nodes</th>
<th>Divergent 10° Cells</th>
<th>Divergent 10° Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>2,088,240</td>
<td>2,193,568</td>
<td>2,061,240</td>
<td>2,164,448</td>
<td>2,185,440</td>
<td>2,298,400</td>
</tr>
<tr>
<td>Medium</td>
<td>4,505,560</td>
<td>5,110,200</td>
<td>4,924,330</td>
<td>5,565,840</td>
<td>4,324,680</td>
<td>4,895,000</td>
</tr>
<tr>
<td>Fine</td>
<td>12,531,330</td>
<td>13,049,888</td>
<td>12,315,330</td>
<td>12,825,548</td>
<td>13,308,930</td>
<td>13,857,972</td>
</tr>
</tbody>
</table>

With the arytenoid structure, three types of grids were used in the simulations. The coarse grids contained between $2 \times 10^6$ and $2.2 \times 10^6$ cells. The medium and fine meshes were established as applied to the cases without the arytenoid structure. Table 2.3 presents the characteristics of each mesh for all cases (uniform, convergent, and divergent glottal shapes with the arytenoid structure).

The fine grids included between $12.3 \times 10^6$ and $13.4 \times 10^6$ cells which required much computational time and memory space. In order to minimize the computational effort, the flow domain was limited to a short distance (1.3 mm, real life) downstream of the vocal folds (for the cases without the arytenoid structure) and a short distance (1.3 mm, real life) downstream of the arytenoid (for the cases with the arytenoid structure). This was equal to 10 mm in the scaled-up model. This simplification was justified by the measured pressure data in the tunnel, which showed constant pressures along the tunnel downstream of the larynx.

It is noted that for the series of cases with a uniform glottis but different diameters, the same number of cells and nodes for the largest uniform case (0.16 cm) shown in Tables 2.2 and 2.3 were used. Thus, the cell sizes were smaller for the uniform cases with glottal diameters of 0.04 and 0.01 cm. The simulations were run on the OSC (Ohio Supercomputer Center) clusters, as well as on a Linux 64-bit machine.
Figure 2-14: Three-dimensional structured mesh of the computational glottal model flow field (airway) for the cases with the arytenoid structure (one half of the low-resolution mesh is shown).
Chapter 3

Results: Pressure Distributions and Volume Flow

3.1 Introduction

The experimental apparatus (M6), described in chapter 2, was used to acquire all the empirical data for pressure distributions along the vocal folds. These experimental data are included to be used in multi-mass models of phonation as well as used by others to validate computational models of phonation.

The graphs are presented in two sections corresponding to the different glottal angles and diameters cases (see section 2.1.2.2). There were two setups, with and without the arytenoid structure. For each setup, the pressure distributions were obtained for the representative transglottal pressures of 0.294, 0.491, 0.981, 1.472, 1.962, and 2.453 kPa (i.e., 3, 5, 10, 15, 20, and 25 cm H$_2$O). Furthermore, for each case, there were three different rows of pressure distribution data (anterior (1/4), middle, and posterior (3/4)). Each set of data was compared to FLUENT simulations.

The main question asked in this study was: how do the pressure distributions in the three-dimensional glottis with vocal fold curvature vary in the anterior-posterior
direction for (a) different glottal angles, (b) different glottal diameters, and (c) with and without the arytenoid cartilages structure. Therefore, results will be presented in two sections. In the first part (Section 3.2), the experimental data for different glottal angles are compared and discussed. In these cases, the glottal angles were 10° convergent, 0° uniform, and 10° divergent, all with a glottal diameter of 0.16 cm. In the second part (Section 3.3), the glottal diameters were 0.01, 0.04, and 0.16 cm, all with a uniform glottal angle.

Table 3.1 indicates the consistent use of symbols and lines to display data and numerical simulations, respectively, in the forthcoming figures. Table 3.2 provides the acronyms for each case (of angle and diameter) in each graph.

In this study, the name for the data in each graph for all the series follows a standard format of coding. The common format is AAA-BB-CC-DDD-EEE, where AAA represents the angle and diameter of each case. For instance, C16 represents the case characterized by convergent 10° glottal angle and a diameter of 0.16 cm in real-life. BB represents with arytenoid structure (WA) or no arytenoid structure (NA). CC indicates the transglottal pressure applied to each case. For the sake of coding simplicity, these pressure values are given in cm H\textsubscript{2}O instead of kPa values, but they are easily interchangeable. DDD gives the position of each row (MID stands for middle row, ANT for anterior (1/4) row, and POS for posterior (3/4) row), and finally EEE shows the type of data (NUM stands for numerical data and EXP for experimental data). For the uniform glottis case with the smallest diameter (U01), there was flow skewness, which means that the airflow tilted from the center-line, and therefore two distinct pressure distributions were obtained, each designated by an acronym (FW stands for flow-wall, and NFW for non-flow-wall).

Two distinct examples are now presented and explained to illustrate this coding format. C16-NA-10-ANT-EXP means the set of data belongs to a convergent case (C) with the diameter of 0.16 cm (real-life), without arytenoid structure (NA), at a
Table 3.1: Standard of line styles and symbols used for the three different rows in the experimental and numerical results.

<table>
<thead>
<tr>
<th>Row</th>
<th>Experimental data (Symbols)</th>
<th>Numerical data (Line)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>△</td>
<td>dash-dot</td>
</tr>
<tr>
<td>Middle</td>
<td>○</td>
<td>solid</td>
</tr>
<tr>
<td>Posterior</td>
<td>▽</td>
<td>dash-dot-dot</td>
</tr>
</tbody>
</table>

Table 3.2: Acronyms for the five different glottal configurations used in the figures.

<table>
<thead>
<tr>
<th>Case</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convergent-0.16 cm</td>
<td>C16</td>
</tr>
<tr>
<td>Divergent-0.16 cm</td>
<td>D16</td>
</tr>
<tr>
<td>Uniform-0.16 cm</td>
<td>U16</td>
</tr>
<tr>
<td>Uniform-0.04 cm</td>
<td>U04</td>
</tr>
<tr>
<td>Uniform-0.01 cm</td>
<td>U01</td>
</tr>
</tbody>
</table>

transglottal pressure of 10 cm H$_2$O (0.981 kPa), and acquired in the anterior (1/4) row (ANT) experimentally (EXP). Similarly, U04-WA-25-MID-NUM means that this set of data is for numerical results in the middle row at a transglottal pressure of 25 cm H$_2$O (2.453 kPa) for the condition that the arytenoid structure was used and the glottis was are uniform (0°) for a diameter of 0.04 cm (real-life).

### 3.2 Variable Glottal Angles

The cases with different glottal angles are discussed in this section. The glottal angles were 10° convergent, 0° uniform, and 10° divergent. For each case, the intraglottal pressure distributions are presented for the minimum transglottal pressure of 0.294 kPa (3 cm H$_2$O) separately. The intraglottal pressure distributions for the other transglottal pressures (0.491 to 2.453 kPa) were similar to those for 0.294 kPa and
are presented near the end of the next two sections. The three different glottal angles were compared with each other and will be discussed below. The glottal angle effects were studied in two different conditions, with and without the arytenoid cartilages structure. For all cases where glottal angle was varied, the minimal glottal diameter in the midcoronal plane was 0.16 cm.

3.2.1 Without arytenoid structure

3.2.1.1 Results

Figure 3-1 presents both the experimental data (symbols) and the computational predictions from FLUENT (lines). It shows the results for a transglottal pressure of 0.294 kPa (3 cm H₂O) for the glottal angle of 10° convergent case (C16). The pressures on the inferior vocal fold surface (taps #1-5) decreased as the cross sectional area of the region reduced. The pressures at corresponding taps for both the anterior (1/4) and posterior (3/4) distributions were nearly identical (due to the symmetry of the geometry relative to the midsagittal plane of the glottal airway).

Intraglottal pressures decreased from tap #6 (at the glottal entrance) toward the glottal exit, were lowest at tap #11 where the minimal glottal diameter is located, and then rose, consistent with pressure recovery, in the short curvature toward the glottal exit proper, with pressures at tap #12 nearly equal to the pressures on top of the vocal folds (taps #13 and #14) near the glottal exit. The middle section pressure distribution consistently showed values less than for the other two distributions (anterior (1/4) and posterior (3/4) sections) up to tap #9, beyond which the values for all three locations coincided. The pressure difference between the distributions at tap #6 was 11 Pa, or 4% of the transglottal pressure, suggesting that, at the glottal entrance (and upstream on much of the inferior glottal surface), a smaller lateral force ("push") acted on the wall at the middle of the vocal fold than at the anterior
Figure 3-1: Experimental and numerical pressure distributions for the convergent 10° case (C16) without the arytenoid structure at the three sections for $\Delta p_T = 0.294$ kPa (3 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
(1/4) and posterior (3/4) sections. The “push” difference, however, was small, and the pressures became essentially the same on the vocal fold surface starting near the downstream center of the glottis at all three locations. The comparison with experimental data showed that the FLUENT values (the continuous lines in the figure) were excellent approximations for the convergent case. The computational results also suggested a slight dip in the pressures just before tap #6, and a greater pressure dip just past tap #11.

Relative to the divergent 10° case (D16) in Fig. 3-2, the relation among the pressure distributions was similar to the convergent case in that the center pressure at (and upstream of) tap #6 was lower than for the pressure in the anterior (1/4) and posterior (3/4) sections. The difference in pressure was 12 Pa, or 4.1% of the transglottal pressure at tap #6. From tap #7 trough #10, the middle tap pressure was also lower than at the other two locations, less than about 3%. The rise in pressure from tap #6 to the glottal exit, using the middle distribution, was 78 Pa, or 27% of the transglottal pressure. The computational predictions were slightly lower than both pressures at tap #6, the location of the greatest change in contour in the model (i.e., at the divergence entrance), but matched the empirical data better downstream of tap #6.

The pressure distributions for the uniform glottis case (U16) are presented in Fig. 3-3. The pressures have a local minimum at tap #6, rising to tap #7, and then decreasing to tap #11, with the pressure recovery again at the end of the glottis, as expected due to the rounded exit. It is noted that even though the duct was uniform, the diameter was 0.16 cm (real life) at the maximum glottal width, with a glottal duct length in the inferior-to-superior direction of 0.3 cm. Thus, the glottal duct was not aerodynamically long to setup a linear pressure drop, satisfying a Poiseuille distribution, but instead produced the pressure dip at tap #6. Contrary to the convergent case, the pressures at tap #6 were approximately equal for the distributions
Figure 3-2: Experimental and numerical pressure distributions for the divergent 10° case (D16) without the arytenoid structure at the three sections for $\Delta p_T = 0.294$ kPa (3 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-3: Experimental and numerical pressure distributions for the uniform 0° case (U16) without the arytenoid structure at the three sections for $\Delta p_T = 0.294$ kPa (3 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
at the three locations (anterior (1/4), middle (1/2), posterior (3/4)); from tap #7 to tap #11, pressures for the middle distribution were slightly higher than for the other two distributions (by at most 9 Pa, or 3% of the transglottal pressure).

3.2.1.2 Discussion

The comparison of measured and computational flow estimations are shown in Table 3.3. The greatest difference between the empirical and computational results (using the fine mesh) was 4.7% for the convergent 0.294 kPa case. Overall the average difference between experimental and FLUENT data was 1.7% (standard deviation of 1.1%). This suggests that FLUENT predicted the flow rates well.

The pressure distributions for the other transglottal pressures ($\Delta p_T = 0.491, 0.981, 1.472, 1.962, \text{ and } 2.453 \text{ kPa}$), shown in Fig. 3-5 to Fig. 3-9, were typical for the three glottal shapes at 0.294 kPa already shown but presented again in Fig. 3-4. The following observations are made:

a) The shape of the experimental and computational pressure distributions were similar to the 0.294 kPa case presented above, for each of the glottal angles.

b) For the convergent case, the difference between the middle and the other pressure distributions (i.e., anterior (1/4) and posterior (3/4) sections) at the glottal entrance tap #6 were similar, ranging from 4.0% to 5.2% of the transglottal pressure (mean of 4.9%, S.D. 0.34%).

c) For the uniform case, the pressure at glottal entrance tap #6 was lower than at tap #7 for the distribution at all three locations, and the largest intraglottal pressure difference between the middle and other two locations was again similar and small (with a range of 2.0% to 3.2% of the transglottal pressure, mean of 2.7%, S.D. 0.42%), with the middle distribution values higher than the other two distribution values.

d) The middle distribution pressure values at tap #6 for the divergent cases were consistently lower than for the distributions at the other two locations, with a range of
difference from 2.6% to 7.4% of the transglottal pressure (mean of 5.6%, S.D. 1.7%).

e) The pressure rise (recovery) between tap #6 and tap #14 for the divergent glottis was also similar among the five different transglottal pressures, with a range of 26% to 30% (mean of 28%, S.D. only 1.5%).

Table 3.3: M6 glottal flows (in cm$^3$/s, real life), without the arytenoid structure, for different values of the transglottal pressure, $\Delta p_T$: comparison between experimental data and computational results. The computational results are presented for three grids (see Table 2.2): coarse (C), medium (M), and fine (F).

<table>
<thead>
<tr>
<th>$\Delta p_T$ [kPa]</th>
<th>Convergent 10°</th>
<th>Uniform</th>
<th>Divergent 10°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp'l (C)</td>
<td>Comp (M)</td>
<td>Exp'l (C)</td>
</tr>
<tr>
<td>0.294</td>
<td>257.8</td>
<td>268.9</td>
<td>270.5</td>
</tr>
<tr>
<td>0.491</td>
<td>344.4</td>
<td>349.3</td>
<td>351.8</td>
</tr>
<tr>
<td>0.981</td>
<td>488.9</td>
<td>497.2</td>
<td>501.4</td>
</tr>
<tr>
<td>1.472</td>
<td>611.1</td>
<td>610.9</td>
<td>616.4</td>
</tr>
<tr>
<td>1.962</td>
<td>700.7</td>
<td>707.0</td>
<td>713.2</td>
</tr>
<tr>
<td>2.453</td>
<td>793.3</td>
<td>791.7</td>
<td>798.5</td>
</tr>
</tbody>
</table>

3.2.2 With arytenoid structure

3.2.2.1 Results

Figure 3-10 shows both the experimental results and the computational results for a transglottal pressure of 0.294 kPa (3 cm H$_2$O) for the glottal angle of 10° convergent case (C16) when the arytenoid structure replaced the long slab posterior to the vocal folds. When the arytenoid structure is present, the glottis is an eccentric (off-center) orifice relative to the airway. Similar to the convergent case without the arytenoid structure, the pressures on the inferior vocal fold surface (taps #1-5) decreased as the cross sectional area of the region reduced, but the pressures at corresponding taps for both the anterior (1/4) and posterior (3/4) distributions were slightly different due
Figure 3-4: Experimental and numerical pressure distributions for the three glottal angles without the arytenoid structure at the three sections for $\Delta p_T = 0.294$ kPa (3 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-5: Experimental and numerical pressure distributions for the three glottal angles without the arytenoid structure at the three sections for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-6: Experimental and numerical pressure distributions for the three glottal angles without the arytenoid structure at the three sections for $\Delta p_T = 0.981$ kPa ($10 \text{ cm H}_2\text{O}$). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-7: Experimental and numerical pressure distributions for the three glottal angles without the arytenoid structure at the three sections for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-8: Experimental and numerical pressure distributions for the three glottal angles without the arytenoid structure at the three sections for $\Delta p_T = 1.962$ kPa (20 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-9: Experimental and numerical pressure distributions for the three glottal angles without the arytenoid structure at the three sections for $\Delta p_T = 2.453$ kPa (25 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
to the eccentricity of the glottis. Also, contrary to the convergent case without the arytenoid structure, the FLUENT results suggest that there was an abrupt gradient change of the pressure distributions on the inferior vocal fold surface between tap #4 and tap #5.

Intraglottal pressures were approximately the same for taps #6 and #7 (Fig. 3-10), then decreased to tap #11, and then rose toward the glottal exit. Like the case without the arytenoid structure, the middle section pressures at taps #6 and #7 were lower than at the anterior (1/4) and posterior (3/4) locations. Unlike the case without the arytenoid structure (Fig. 3-1), however, the middle location values for pressure taps #8 - #10 were between those for the anterior (1/4) and posterior (3/4), with the anterior (1/4) pressures being the highest. The difference between the pressures of the middle and posterior (3/4) sections at tap #6 was 9 Pa, or 3% of the transglottal pressure, and between the posterior (3/4) and anterior (1/4) sections was 6 Pa, or 2%. Thus, the pressure difference between the middle and anterior (1/4) sections was 15 Pa, or 5% of the transglottal pressure drop. Then at tap #11, the middle section once again was lower than the other two sections (which were essentially the same). To summarize for the 10° convergent case, at the glottal entrance and on the inferior surface of the vocal fold, although the differences were small, a smaller force acted on the wall at the middle of the vocal fold, and within the glottis, (a) pressures were lowest at the middle section at glottal entrance, (b) there was an anterior-posterior pressure gradient for taps #8 - #10 with pressures highest anteriorly and lowest posteriorly, (c) near the exit rounding, tap #11, again the middle pressure was lowest, and (d) pressures were the same through the rounded exit. Similar to the case without the arytenoid structure, the computational results showed a dip in the pressures just before tap #6 and just past tap #11.

Figure 3-11, relative to the divergent 10° case (D16) with the arytenoid structure, showed that the general forms of the pressure distributions along the vocal fold were
Figure 3-10: Experimental and numerical pressure distributions for the convergent 10° case (C16) with the arytenoid structure at the three sections for $\Delta p_T = 0.294$ kPa ($3 \text{ cm H}_2\text{O}$). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
similar to the case without the arytenoid structure, but the behaviors of the ante-
rior (1/4) and posterior (3/4) sections were different. The middle pressure at (and 
upstream of) tap #6 was lower than for the pressure in the anterior (1/4) and pos-
terior (3/4) sections. The pressure of the anterior (1/4) and posterior (3/4) sections 
on the inferior surface of the vocal fold were essentially equal, but near the glottal 
entrance (between tap #5 and tap #6), the anterior (1/4) section pressure decreased 
approximately to the middle section pressure from tap #6 to tap #11, the pressure of 
the anterior (1/4) section tending to be slightly lower than the pressure of the middle 
section, and the posterior (3/4) was significantly higher than both the other pressures 
(by about 24 Pa or 8% of the transglottal pressure at tap #6). The pressure rose 
from tap #6 to the glottal exit (tap #14), and using the middle distribution, was 
88 Pa, or 30% of the transglottal pressure. Similar to the case without the arytenoid 
structure, the computational predictions were slightly lower than empirical data at 
tap #6, but matched better downstream of tap #6.

To summarize for the divergent 10° case, the pressures on the inferior vocal fold 
surfaces were lower along the middle pressure distribution than either anterior (1/4) 
or posterior (3/4) locations, and within the glottis, (a) the posterior (3/4) pressure 
was significantly higher than for the other two locations at glottal entrance and re-
mained higher from tap #6 to tap #11, (b) the anterior (1/4) pressures tended to be 
slightly lower than the middle location pressures, and thus (c) there was an anterior-
posterior pressure gradient in the glottis, with posterior (3/4) pressures being highest 
(a condition just opposite to that seen for the convergent 10° case).

The eccentricity of the glottis also created significant differences for the uniform 
glottis. Although, there were again two dips in all three pressure distributions for 
the different locations, one at tap #6 and one at tap #11 (compare Fig. 3-12 with 
Fig. 3-3), the pressures at tap #6 had different values for the three locations for 
the eccentric case, unlike the non-eccentric case. These values were still zero for the
Figure 3-11: Experimental and numerical pressure distributions for the divergent 10° case (D16) with the arytenoid structure at the three sections for $\Delta p_T = 0.294$ kPa ($3 \text{ cm H}_2\text{O}$). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
middle section, but 11 Pa (3.7%) for the posterior (3/4), and -10 Pa (3.4%) for the anterior (1/4) section. The pressures on the inferior vocal fold surface (taps #1-5) decreased as the cross sectional area of the region reduced, and the anterior (1/4) pressures essentially equaled the posterior (3/4) pressures up to tap #4, but were lower at tap #5.

The pressure at all three locations rose from tap #6 to tap #7, and then decreased to tap #11. In this part of the glottis, the pressures of the middle and posterior (3/4) sections essentially were identical and both higher than the pressure of the anterior (1/4) section (by at most 13 Pa, or 4.5% of the transglottal pressure). The pressure values for all three locations from tap #11 to #14 coincided, with the usual recovery from tap #11 to #14. In summary for the uniform glottis, the pressures on the inferior vocal fold surface were lower for the middle tap locations, with the anterior (1/4) pressures lower than the posterior (3/4) pressures near glottal entry, and within the glottis, (a) the posterior (3/4) pressure was higher than the other two at glottal entry where a definite anterior-posterior pressure gradient was evident, (b) the anterior (1/4) pressures were lower than the nearly identical middle and posterior (3/4) pressures from tap #7 to #10, and thus (c) the pressure gradient in the anterior-posterior direction was more similar to the divergent case (anterior (1/4) pressures least) than to the convergent case (anterior (1/4) pressures slightly higher).

3.2.2.2 Discussion

Table 3.4 compares the measured and computational flow estimations for the eccentric cases. The convergent case had the highest difference between empirical (lower) and computational (higher) results (using the fine mesh) with the value of 5.5% for the transglottal pressure of 0.294 kPa. Overall the average difference between experimental and FLUENT flow values was low, only 2.1% (S.D. 1.4%). In addition, the empirical flows for the same transglottal pressure were lower for the cases with
Figure 3-12: Experimental and numerical pressure distributions for the uniform 0° case (U16) with the arytenoid structure at the three sections for $\Delta p_T = 0.294 \text{ kPa} (3 \text{ cm H}_2\text{O})$. Note that the ANT and POS pressures were nearly identical and thus closely overlap.
the arytenoid structure (Table 3.4) than for the cases without the arytenoid structure (Table 3.3), with the interpretation that the presence of the arytenoid created greater flow resistance (ranging from 0.9% to 9.7%, average of 4.5%). Thus, the arytenoid cartilages structure itself increased the flow resistance by about 5%. The pressure distributions for the other transglottal pressures ($\Delta p_T = 0.491, 0.981, 1.472, 1.962, \text{ and } 2.453 \text{ kPa}$) are shown in Fig. 3-14 to Fig. 3-18. The following observations were made for the cases of different glottal angles and the presence of the arytenoid structure:

a) The shape of the experimental and computational pressure distributions were similar to the 0.294 kPa case presented above, for each of the glottal angles.

b) For the convergent case, the general shape of the intraglottal pressures did not change much when the arytenoid structure was considered, but an abrupt pressure gradient appeared just past tap #4 on the inferior vocal fold surface. At the glottal entrance, the anterior ($1/4$) pressures were higher than the posterior ($3/4$) pressures from 2.0% to 2.4% of the transglottal pressure (mean of 2.2%, S.D. 0.27%). Also, the posterior ($3/4$) pressures were higher than the middle pressures from 2.6% to 3.1% of the transglottal pressure (mean of 2.75%, S.D. 0.31%). Past the entrance to the glottis an anterior-posterior pressure gradient, with highest pressures anteriorly, lowest pressures posteriorly, was evident, although the gradient was small.

c) For the uniform case, the pressures at glottal entrance tap #6 were lower than at tap #7 for the distributions at all three locations, creating two dips in the pressure distributions, one at entry and the other near tap #11. Contrary to the case without the arytenoid structure, for the case with the arytenoid structure at tap #6, the three pressure values were different; the posterior ($3/4$) location had the highest value and the anterior ($1/4$) location had the lowest value, creating an anterior-posterior pressure gradient in the glottis. Beyond the glottal entrance, the middle and posterior ($3/4$) pressures were nearly the same. The largest intraglottal
pressure difference between the anterior (1/4) and the other two locations (middle and posterior) ranged between 3.8% to 4.5% of the transglottal pressure (mean of 4.1%, S.D. 1.1%), with the middle and posterior (3/4) distribution values higher than the anterior (1/4) distribution values. Thus, there was a pressure gradient primarily in the anterior half of the glottis, with pressures lower anteriorly.

d) In the divergent case, the middle and anterior (1/4) pressure values were almost identical at tap #6 and were consistently lower than for the pressures for the posterior (3/4) locations, with a range of significant differences from 6.0% to 8.7% of the transglottal pressure (mean of 7.8%, S.D. 2.4%). Thus, there was a significant anterior-posterior glottal pressure gradient with pressures lower anteriorly, something like that found for the uniform case. The pressure rise (recovery) between tap #6 and tap #14 for the divergent glottis in the middle location was also similar among the five different transglottal pressures, with a range of 30% to 32% (mean of 31%, S.D. only 1.4%).

Table 3.4: M6 glottal flows (in cm$^3$/s, real life), with the arytenoid structure, for different values of transglottal pressure, $\Delta p_T$: comparison between experimental data and computational results. The computational results are presented for three grids (see Table 2.3): coarse (C), medium (M), and fine (F).

<table>
<thead>
<tr>
<th>$\Delta p_T$ [kPa]</th>
<th>Convergent 10°</th>
<th>Uniform</th>
<th>Divergent 10°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp’l</td>
<td>Comp</td>
<td>Exp’l</td>
</tr>
<tr>
<td></td>
<td>(C)</td>
<td>(M)</td>
<td>(F)</td>
</tr>
<tr>
<td>0.294</td>
<td>233.3</td>
<td>245.7</td>
<td>251.2</td>
</tr>
<tr>
<td>0.491</td>
<td>311.1</td>
<td>334.1</td>
<td>335.2</td>
</tr>
<tr>
<td>0.981</td>
<td>466.7</td>
<td>475.6</td>
<td>480.1</td>
</tr>
<tr>
<td>1.472</td>
<td>583.3</td>
<td>587.5</td>
<td>591.5</td>
</tr>
<tr>
<td>1.962</td>
<td>677.8</td>
<td>684.1</td>
<td>692.3</td>
</tr>
<tr>
<td>2.453</td>
<td>777.8</td>
<td>775.1</td>
<td>787.8</td>
</tr>
</tbody>
</table>

60
Figure 3-13: Experimental and numerical pressure distributions for the three glottal angles with the arytenoid structure at the three sections for $\Delta p_T = 0.294$ kPa ($3$ cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-14: Experimental and numerical pressure distributions for the three glottal angles with the arytenoid structure at the three sections for $\Delta p_T = 0.491$ kPa ($5 \text{ cm H}_2\text{O}$). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-15: Experimental and numerical pressure distributions for the three glottal angles with the arytenoid structure at the three sections for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-16: Experimental and numerical pressure distributions for the three glottal angles with the arytenoid structure at the three sections for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-17: Experimental and numerical pressure distributions for the three glottal angles with the arytenoid structure at the three sections for $\Delta p_T = 1.962$ kPa ($20 \text{ cm } H_2O$). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-18: Experimental and numerical pressure distributions for the three glottal angles with the arytenoid structure at the three sections for $\Delta p_T = 2.453$ kPa (25 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
3.3 Variable Glottal Diameters

In this section, the cases with different glottal diameters are presented. The chosen glottal diameters were 0.16 cm, 0.04 cm, and 0.01 cm (real-life). For each case, the glottal shape was uniform (a glottal angle of 0°). The intraglottal pressure distributions will be presented for the minimum transglottal pressure of 0.294 kPa (3 cm H₂O). The intraglottal pressure distributions for the other transglottal pressures (0.491 to 2.453 kPa) were similar to those for 0.294 kPa. The glottal diameter effects were studied for two different conditions, with and without the arytenoid structure.

3.3.1 Without arytenoid structure

3.3.1.1 Results

The pressure distributions for the case when the arytenoid cartilages structure was not included are presented in Fig. 3-19 for the diameters of 0.01, 0.04, and 0.16 cm. Both the empirical pressure distributions (represented by symbols) and the corresponding computational pressure distributions (represented by lines) are shown for a transglottal pressure of 0.294 kPa (3 cm H₂O). As before, there were three sets of experimental pressure distributions for each glottal diameter, corresponding to the three coronal sections. For all three diameter cases, the pressures on the inferior vocal fold surface (taps #1-5) decreased as the cross sectional area of the region reduced. Since the larynx was symmetrical, it was expected that the pressures also might be symmetrical anterior (1/4) and posterior (3/4) to the midcoronal section. This prediction was relatively accurate; the pressure distributions at the anterior (1/4) and posterior (3/4) cross sections were found to be highly similar (seen as overlapping data points in the figures) except for tap #6 and #7 for 0.01 cm and tap #6 for 0.04 cm, where the posterior (3/4) pressure was higher by approximately 3% of the transglottal pressure at tap #6 for 0.01 cm, and the anterior (1/4) pressure
higher by approximately 2% at tap #6 for 0.04 cm.

For case U01 (smallest diameter, Fig. 3-19), the intraglottal pressures decreased from tap #6 (at the glottal entrance), with the minimum value recorded at tap #11, after which a small pressure recovery took place to the glottal exit. The pressure difference between the mid section and the anterior (1/4) section at tap #6 was 16.5 Pa, or 5.7% of the transglottal pressure, and about 12% at tap #7. There was a small unexpected difference between the anterior (1/4) and posterior (3/4) pressures (about 2.5% or less of the transglottal pressure) for taps #6 to #11 for (only) transglottal pressures of 0.294 kPa (3 cm H$_2$O) and 0.491 kPa (5 cm H$_2$O). The differences were unexpected because of the symmetry of the vocal folds (that is, this is the case without the arytenoid structure producing eccentricity of the glottis). Since there was no logical reason for a difference, and for the higher transglottal pressures the simulation data showed good agreement with the experimental results, we were confident in the accuracy of the results. Thus, we suspect that these small differences were “construction error” or partially clogged passageways for those taps, or within measurement error in general. The drop in pressure from tap #6 to the glottal exit for the middle distribution was 0.137 kPa, or 47% of the transglottal pressure. Also, the pressures of the middle section up to tap #11 were significantly lower than those obtained in the anterior (1/4) and posterior (3/4) sections, suggesting that intraglottal pressures would push the vocal folds with least force at the midcoronal location when the diameter is small.

The trend for the pressure distributions for case U04 was similar to that observed for case U01 up to tap #11 (Fig. 3-19). The mid-section pressure at tap #6 (and upstream of #6) was lower than the corresponding pressures at the anterior (1/4) and posterior (3/4) locations. The difference in pressure was 13 Pa (or 4.5% of the transglottal pressure) at tap #6. On the middle distribution, the drop in pressure from tap #6 to the glottal exit was 0.094 kPa, or 32% of the transglottal pressure.
Figure 3-19: Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), without the arytenoid structure at the three sections for $\Delta p_T = 0.294$ kPa (3 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
The pressure gradient from the glottal entrance to tap #11 was less for diameter 0.04 cm than for 0.01 cm.

The shape of the pressure distributions for case U16 was different from that observed for cases U01 and U04 for which the pressures generally decreased continuously up to tap #11. For case U16 (presented earlier in Section 3.3.1.1) the pressure distributions showed a local minimum at tap #6, rising to tap #7, and then decreased to tap #11, with the pressure recovery again at the end of the glottis due to the rounded exit (see Fig. 3-19). Contrary to cases U01 and U04, the pressures at tap #6 were approximately equal for all three coronal tap locations (anterior (1/4), middle, posterior (3/4)). Also contrary to cases U01 and U04, between taps #7 and tap #11, the pressures for the middle distribution were slightly higher (rather than lower) than for the other two distributions (by at most 9 Pa, or 3% of the transglottal pressure).

For case U01 with the smallest diameter (and not for cases U04 and U16), the flow was seen to skew to one side (called the flow wall side) where flow visualization was used (see Chapter 4 below for flow visualization results). It is speculated that this occurred due to the relatively high aspect ratio of glottal length to maximum glottal diameter (1.2/0.01 = 120), the least curvature gradient of the vocal fold medial surface, and to the lowest flow momentum through the glottis. The flow asymmetry could not be captured in the simulation results because FLUENT software predicts a symmetric flow through a symmetric glottis with symmetric boundary conditions. To generate the skewed flow using FLUENT, a small pressure gradient (linear, 0-0.2 Pa across the duct 1.3 mm (real-life) downstream of the glottis) was imposed as a boundary condition. This method of inducing an artificial non-symmetric flow has been used in earlier studies [37, 38]. The resulting skewed flow simulated by FLUENT gave rise to small pressure differences within the glottis only past the tap #11 location, as shown in Fig. 3-20, where the glottal exit section of Fig. 3-19 for case U01 has been magnified. After tap #11 and before tap #12, the computational results simulated
Figure 3-20: Experimental (symbols) vs. computational (lines) comparison for Flow-Wall (FW) and Non-Flow-Wall (NFW) for the diameters of 0.01 cm (real life) for case (U01), glottal angle of 0° (uniform), for transglottal pressures 0.294 kPa (3 cm H$_2$O). The presented numerical results correspond to the finest mesh in Table 2.2.
flow that skewed throughout this small divergence, such that the flow-wall (FW) and non-flow wall (NFW) pressure distributions were created. The anterior (1/4) and posterior (3/4) pressures were still nearly identical, but different for the FW and the NFW. The maximum difference between the flow wall and non-flow wall at the mid-section was 4 Pa, or 1.3% of the transglottal pressure. The computational pressure values differed from the experimental results at taps #11 and #12 by only approximately 1% of the transglottal pressure.

3.3.1.2 Discussion

The pressure distributions for the other transglottal pressures (0.491 to 2.453 kPa) were similar to those for 0.294 kPa (see Fig. 3-21 to Fig. 3-25). The following observations are made:

a) The shape of the empirical and numerical pressure distributions for all transglottal pressures were similar to the transglottal pressure of 0.294 kPa (3 cm H$_2$O), for each of the glottal diameters.

b) For case U01, the difference between the middle and the other pressure distributions (anterior (1/4), posterior (3/4)) at the glottal entrance tap #6 were similar, ranging from 5.0% to 6.4% of the transglottal pressure (mean of 5.7%, S.D. 0.45%).

c) The middle distribution pressure values at tap #6 for case U04 were consistently lower than for the values at the other two locations, with a range of difference from 4.1% to 4.9% of the transglottal pressure (mean of 4.5%, S.D. 0.28%).

d) For case U16, the pressures at glottal entrance (tap #6) were approximately the same for the distributions at all three locations and were all lower than at tap #7. The largest intraglottal pressure differences between the middle and other two locations were at taps #7-9 and were small (with a range of 2.0% to 3.2% of the transglottal pressure, mean of 2.7%, S.D. 0.42%), with the middle distribution values higher than the other two distribution values.
Table 3.5: M6 glottal flows (in cm$^3$/sec, real-life), without the arytenoid structure, for different values of transglottal pressure, $\Delta p$: comparison between experimental data and computational results. The computational results are presented for three grids (see Table 2.2): coarse (C), medium (M), and fine (F).

<table>
<thead>
<tr>
<th>$\Delta p$ [kPa]</th>
<th>Case (U01) Exp'l (C)</th>
<th>Comp (M)</th>
<th>Comp (F)</th>
<th>Case (U04) Exp'l (C)</th>
<th>Comp (M)</th>
<th>Comp (F)</th>
<th>Case (U16) Exp'l (C)</th>
<th>Comp (M)</th>
<th>Comp (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.294</td>
<td>13.05</td>
<td>13.35</td>
<td>13.51</td>
<td>13.44</td>
<td>58.27</td>
<td>57.23</td>
<td>59.90</td>
<td>59.70</td>
<td>255.6</td>
</tr>
<tr>
<td>0.491</td>
<td>19.51</td>
<td>18.91</td>
<td>20.15</td>
<td>19.94</td>
<td>79.16</td>
<td>78.72</td>
<td>81.16</td>
<td>80.42</td>
<td>333.3</td>
</tr>
<tr>
<td>0.981</td>
<td>32.26</td>
<td>31.54</td>
<td>33.35</td>
<td>32.80</td>
<td>118.6</td>
<td>117.8</td>
<td>120.3</td>
<td>119.4</td>
<td>477.8</td>
</tr>
<tr>
<td>1.472</td>
<td>42.64</td>
<td>42.16</td>
<td>43.87</td>
<td>45.59</td>
<td>149.3</td>
<td>148.6</td>
<td>151.7</td>
<td>149.8</td>
<td>588.9</td>
</tr>
<tr>
<td>1.962</td>
<td>51.87</td>
<td>50.85</td>
<td>53.74</td>
<td>51.94</td>
<td>174.3</td>
<td>172.8</td>
<td>179.2</td>
<td>175.6</td>
<td>677.8</td>
</tr>
<tr>
<td>2.453</td>
<td>59.37</td>
<td>58.22</td>
<td>62.28</td>
<td>60.55</td>
<td>197.9</td>
<td>195.7</td>
<td>203.4</td>
<td>198.8</td>
<td>766.7</td>
</tr>
</tbody>
</table>

The comparison of measured and simulation flow rates are shown in Table 3.5. The values were quite similar. The largest difference was for a transglottal pressure of 0.294 kPa and case U01 where the difference was 2.8%. The average difference between measured and simulation flow was 1.3%, with the experimental flows being less than the simulation flows. Thus, FLUENT predicted the empirical flows well.

3.3.2 With arytenoid structure

3.3.2.1 Results

The empirical pressure distributions and the corresponding numerical data are presented in Fig. 3-26 for a transglottal pressure of 0.294 kPa (3 cm H$_2$O) for the uniform cases with glottal diameters of 0.01, 0.04, and 0.16 cm, respectively. These figures show the pressures when the arytenoid structure was in place, thus creating an eccentric glottis.

Similar to the case without the arytenoid structure, Fig. 3-26 shows that the pressure distributions along the glottal wall for the case with minimum diameter (U01) and with the arytenoid structure decreased from tap #6 (which was located
Figure 3-21: Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), without the arytenoid structure at the three sections for $\Delta p_T = 0.491$ kPa (5 cm $H_2O$). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-22: Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), without the arytenoid structure at the three sections for $\Delta p_T = 0.981$ kPa (10 cm H₂O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-23: Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), without the arytenoid structure at the three sections for $\Delta p_T = 1.472$ kPa (15 cm $H_2O$). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-24: Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), without the arytenoid structure at the three sections for $\Delta p_T = 1.962$ kPa ($20 \text{ cm } H_2O$). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
2.453 kPa (25 cm H₂O)

Figure 3-25: Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), without the arytenoid structure at the three sections for $\Delta p_T = 2.453$ kPa (25 cm H₂O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
at the glottal entrance). The minimum value was recorded at tap #11, after which a pressure recovery took place toward the glottal exit. The pressure was almost totally recovered at tap #12, nearly equal to the pressures on top of the vocal folds (i.e., at taps #13 and #14, axially located at the glottal exit).

The difference in pressure between the middle pressure and the anterior (1/4) pressure at tap #6 was 16 Pa (or 5.5% of the transglottal pressure) for the U01 case. On the middle distribution, the drop in pressure from tap #6 to the glottal exit was 0.135 kPa, or 46% of the transglottal pressure. Comparing these values with the values for the corresponding case without the arytenoid structure (see section 3.2.2.1) showed that the differences were negligible (less than 1%).

It was also observed that, up to tap #11, the pressures in the middle section were lower than those obtained in the anterior (1/4) and posterior (3/4) sections. The numerical results supported that finding, as well. Past this location, according to the FLUENT predictions, the pressures on the left and right walls were slightly different, indicating the presence of flow asymmetries, after applying the 0 - 0.2 Pa pressure gradient across the duct downstream of the glottis. The skewness of the flow was highly similar to that shown for the case without the arytenoid structure. For a clearer view, the glottal exit section of Fig. 3-26 for the case with minimum glottal diameter is magnified in Fig. 3-27, which shows the same trend to as in the case without the arytenoid structure (compare with Fig. 3-20).

Relative to the case with a diameter of 0.04 cm (U04), the medium diameter, the trend of the pressure distributions was similar to that observed for the case (U01) up to tap #11 (Fig. 3-26). Indeed, the mid-section pressure at tap #6 (and upstream of #6) was lower than the corresponding pressures at the anterior (1/4) and posterior (3/4) locations. That is, the pressure difference between the distributions in the mid-coronal section and the anterior/posterior sections at tap #6 was 12.5 Pa, or 4.3% of the transglottal pressure drop. The drop in pressure from tap #6 to the glottal exit,
Figure 3-26: Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), with the arytenoid structure at the three sections for $\Delta p_T = 0.294$ kPa (3 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-27: Experimental (symbols) vs. computational (lines) comparison for Flow-Wall (FW) and Non-Flow-Wall (NFW) for the diameters of 0.01 cm (real life for case (U01), glottal angle of 0° (uniform), for transglottal pressures 0.294 kPa (3 cm H₂O). The presented numerical results correspond to the finest mesh in Table 2.3.
using the middle distribution, was 0.091 kPa, or 31% of the transglottal pressure.

3.3.2.2 Discussion

Table 3.6 shows the comparison of measured and FLUENT flow estimations for the cases where diameter was altered with the arytenoid structure present. For a transglottal pressure of 0.294 kPa, the experimental flow was lower than the FLUENT flow by only 2.7% for case U01, 1.4% for case U04, and 0.1% for case U16, using the finest mesh columns. Overall the average difference between experimental and numerical flow values was low, only 1.1% (S.D. 0.21%). Similar to the cases with different glottal angles (see Section 3.2.2.2), the empirical flows for the same transglottal pressure were lower for the cases with the arytenoid structure present (Table 3.6) than for the cases without the arytenoid structure (Table 3.5). Thus, the presence of the arytenoid created greater flow resistance (range: 1.2%-9.5%, average of 4.7%). Flow resistance was greatest for the uniform case with the smallest glottal diameter (U01) with the arytenoid structure at a transglottal pressure of 2.453 kPa (44.29 kPa/(L/s)) and least for the divergent case (D16) without the arytenoid structure at a transglottal pressure of 0.294 kPa (1.06 kPa/(L/s), see Fig. 3-33).

The following observations were made:

a) The shape of the empirical and FLUENT pressure distributions for all transglottal pressures were similar to the transglottal pressure of 0.294 kPa (see Fig. 3-28 to Fig. 3-32).

b) For the case U01 with the arytenoid structure, the pressure distributions in the anterior (1/4) and posterior (3/4) locations were nearly identical (except at taps #6 and #7 for some of the cases). Similar to the case U01 without the arytenoid structure, there was a small difference between the anterior (1/4) and posterior (3/4) pressures (about 1.2% of the transglottal pressure) at taps #6 and #7 due to assumed mechanical error. The difference between the middle and the other pressure
distributions (anterior (1/4), posterior (3/4)) at the glottal entrance (tap #6) ranged from 5.0% to 6.4% of the transglottal pressure (mean of 5.7%, S.D. 0.45%). Therefore, the intraglottal pressures were similar for the two conditions, with and without the arytenoid structure for the case with minimum diameter (U01).

c) Similar to the case without the arytenoid structure, the middle distribution pressure values at tap #6 for the case U04 with the arytenoid structure were consistently lower than for the distributions at the other two locations, with a range of difference from 4.1% to 4.9% of the transglottal pressure (mean of 4.5%, S.D. 0.28%). The anterior (1/4) and posterior (3/4) pressures were nearly identical and the differences between the pressure distributions along the wall in each row with and without the arytenoid structure were negligible (less than 1%).

d) The pressure drop between tap #6 and tap #11 for the case U04 was also similar among the five different transglottal pressures, with a range of 27% to 35% (mean of 31%, S.D. 0.35%).

e) The flow values were higher for greater transglottal pressure values (as expected), with the difference between the empirical and FLUENT values differing on average by only 1.1% (S.D. 0.21%, with a range of difference between the empirical flow value and the finest mesh runs of 0.5% to 2.1%, see Table 3.6).

f) The case with maximum diameter (U16), was the only case for which pressure distributions significantly changed based on the presence or absence of the arytenoid structure. For this case, contrary to the case without the arytenoid structure, at tap #6, three pressure values were different (maximum at the posterior (3/4) location and minimum at the anterior (1/4)). Middle and posterior (3/4) pressures coincided beyond the glottal entrance. The largest intraglottal pressure difference between the anterior (1/4) and other two locations (middle and posterior (3/4)) was small with a range of 3.8% to 4.5% of the transglottal pressure, mean of 4.1%, S.D. 1.1%), with the middle and posterior (3/4) distribution values higher than the anterior (1/4)
Table 3.6: M6 glottal flows (in cm$^3$/sec, real-life), with the arytenoid structure, for different values of transglottal pressure, $\Delta p$: comparison between experimental data and computational results. The computational results are presented for three grids (see Table 2.3): coarse (C), medium (M), and fine (F).

<table>
<thead>
<tr>
<th>$\Delta p$ [kPa]</th>
<th>Case (U01) Exp’l</th>
<th>Comp</th>
<th>Case (U04) Exp’l</th>
<th>Comp</th>
<th>Case (U16) Exp’l</th>
<th>Comp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(C) (M) (F)</td>
<td></td>
<td>(C) (M) (F)</td>
<td></td>
<td>(C) (M) (F)</td>
<td></td>
</tr>
<tr>
<td>0.294</td>
<td>12.63 13.02 13.13</td>
<td>12.84 55.56 54.45</td>
<td>56.86 56.70 231.3</td>
<td>234.3 236.1 233.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.491</td>
<td>17.94 20.36 20.85</td>
<td>19.94 76.11 75.17</td>
<td>79.49 78.42 306.1</td>
<td>309.3 311.7 310.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.981</td>
<td>30.44 32.95 33.78</td>
<td>32.80 117.2 116.3</td>
<td>119.1 118.5 455.7</td>
<td>458.4 463.3 461.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.472</td>
<td>39.44 42.71 43.65</td>
<td>42.58 145.1 143.7</td>
<td>148.4 147.8 566.2</td>
<td>569.1 579.8 574.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.962</td>
<td>48.44 51.08 51.24</td>
<td>50.91 170.0 167.4</td>
<td>173.9 172.6 659.2</td>
<td>670.3 682.6 674.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.453</td>
<td>55.38 58.48 59.98</td>
<td>57.53 195.0 192.8</td>
<td>199.2 198.8 750.8</td>
<td>757.2 763.9 759.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

g) Flow resistance for both with and without the arytenoid structure varied from about 1 kPa/(L/s) for the lowest transglottal pressure used (0.294 kPa), to about 3 kPa/(L/s) for the highest transglottal pressure (2.453 kPa), for the angle series with glottal diameter of 0.16 cm. For the diameter series, the range was 23 - 44 kPa/(L/s) for U01, 5 - 12 kPa/(L/s) for U04, and again 1 - 3 kPa/(L/s) for U16. The increase in flow resistance with the arytenoid structure in place, versus without arytenoid, was 5 - 10% for the lowest transglottal pressure to only 2% for the highest transglottal pressure for the angle series, and 3 - 8%, 1 - 5%, and again 2 - 10% for the U01, U04, and U16 diameter series, respectively (see Fig. 3-33).
Figure 3-28: Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), with the arytenoid structure at the three sections for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-29: Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), with the arytenoid structure at the three sections for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-30: Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), with the arytenoid structure at the three sections for $\Delta p_T = 1.472$ kPa ($15 \text{ cm } H_2O$). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-31: Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), with the arytenoid structure at the three sections for $\Delta p_T = 1.962$ kPa (20 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
Figure 3-32: Experimental and numerical pressure distributions for the three glottal diameters, glottal angle of 0° (uniform), with the arytenoid structure at the three sections for $\Delta p_T = 2.453$ kPa (25 cm H$_2$O). Note that the ANT and POS pressures were nearly identical and thus closely overlap.
| P (Pa) | Flow\textsubscript{NA} CC/S | Flow (WA) CC/S | R (NA) kPa/(L/S) | R (WA) kPa/(L/S) | (ΔR\textsubscript{s})/R(NA) | Flow\textsubscript{NA} CC/S | Flow (WA) CC/S | R (NA) kPa/(L/S) | R (WA) kPa/(L/S) | (ΔR\textsubscript{s})/R(NA) |
|--------|----------------------------|----------------|----------------|----------------|----------------|----------------------------|----------------|----------------|----------------|----------------|----------------|
| 294    | 257.8                      | 233.3          | 1.140          | 1.260          | 0.105          | 269.9                      | 246.15         | 1.089          | 1.194          | 0.096          |
| 491    | 344.4                      | 311.1          | 1.426          | 1.578          | 0.107          | 351                        | 319.4          | 1.399          | 1.537          | 0.099          |
| 981    | 488.9                      | 466.7          | 2.007          | 2.102          | 0.048          | 500.2                      | 478.3          | 1.961          | 2.051          | 0.046          |
| 1472   | 611.1                      | 583.3          | 2.409          | 2.524          | 0.048          | 614.7                      | 588.6          | 2.395          | 2.501          | 0.044          |
| 1962   | 700.7                      | 677.8          | 2.800          | 2.895          | 0.034          | 711.2                      | 690            | 2.759          | 2.843          | 0.031          |
| 2453   | 793.3                      | 777.8          | 3.092          | 3.154          | 0.020          | 796.3                      | 783.6          | 3.080          | 3.130          | 0.016          |
|        |                            |                |                |                |                |                            |                |                |                |                |
| P (Pa) | Flow\textsubscript{NA} CC/S | Flow (WA) CC/S | R (NA) kPa/(L/S) | R (WA) kPa/(L/S) | (ΔR\textsubscript{s})/R(NA) | Flow\textsubscript{NA} CC/S | Flow (WA) CC/S | R (NA) kPa/(L/S) | R (WA) kPa/(L/S) | (ΔR\textsubscript{s})/R(NA) |
| 294    | 277.8                      | 262.2          | 1.058          | 1.121          | 0.059          | 287.3                      | 273.5          | 1.023          | 1.075          | 0.050          |
| 491    | 366.7                      | 351.1          | 1.339          | 1.398          | 0.044          | 374.2                      | 362.9          | 1.312          | 1.353          | 0.031          |
| 981    | 522.2                      | 515.5          | 1.879          | 1.903          | 0.013          | 533.3                      | 526.3          | 1.839          | 1.864          | 0.013          |
| 1472   | 633.3                      | 620            | 2.324          | 2.374          | 0.021          | 640.3                      | 627.4          | 2.299          | 2.346          | 0.021          |
| 1962   | 722.2                      | 715.5          | 2.717          | 2.742          | 0.009          | 732.8                      | 733.4          | 2.658          | 2.675          | 0.007          |
| 2453   | 788.9                      | 769.5          | 3.109          | 3.188          | 0.025          | 800.9                      | 786.3          | 3.063          | 3.120          | 0.019          |
|        |                            |                |                |                |                |                            |                |                |                |                |
| P (Pa) | Flow\textsubscript{NA} CC/S | Flow (WA) CC/S | R (NA) kPa/(L/S) | R (WA) kPa/(L/S) | (ΔR\textsubscript{s})/R(NA) | Flow\textsubscript{NA} CC/S | Flow (WA) CC/S | R (NA) kPa/(L/S) | R (WA) kPa/(L/S) | (ΔR\textsubscript{s})/R(NA) |
| 294    | 58.27                       | 55.56          | 5.045          | 5.292          | 0.049          | 59.7                        | 56.7           | 4.925          | 5.185          | 0.053          |
| 491    | 79.16                       | 76.11          | 6.203          | 6.451          | 0.040          | 80.42                       | 78.2           | 6.105          | 6.261          | 0.026          |
| 981    | 118.6                       | 117.2          | 8.272          | 8.370          | 0.012          | 119.4                       | 118.5          | 8.216          | 8.278          | 0.008          |
| 1472   | 149.3                       | 145.1          | 9.859          | 10.145         | 0.029          | 149.8                       | 147.8          | 9.826          | 9.959          | 0.014          |
| 1962   | 174.3                       | 170            | 11.256         | 11.541         | 0.025          | 175.6                       | 172.6          | 11.173         | 11.367         | 0.017          |
| 2453   | 197.9                       | 195            | 12.395         | 12.579         | 0.015          | 198.8                       | 198.8          | 12.339         | 12.339         | 0.000          |
|        |                            |                |                |                |                |                            |                |                |                |                |
| P (Pa) | Flow\textsubscript{NA} CC/S | Flow (WA) CC/S | R (NA) kPa/(L/S) | R (WA) kPa/(L/S) | (ΔR\textsubscript{s})/R(NA) | Flow\textsubscript{NA} CC/S | Flow (WA) CC/S | R (NA) kPa/(L/S) | R (WA) kPa/(L/S) | (ΔR\textsubscript{s})/R(NA) |
| 294    | 13.05                       | 12.63          | 22.529         | 23.278         | 0.033          | 13.44                       | 12.84          | 21.875         | 22.897         | 0.047          |
| 491    | 19.51                       | 17.94          | 25.167         | 27.369         | 0.088          | 19.94                       | 19.94          | 24.624         | 24.624         | 0.000          |
| 981    | 32.62                       | 30.44          | 30.409         | 32.272         | 0.060          | 32.8                        | 32.8           | 29.909         | 29.909         | 0.000          |
| 1472   | 42.64                       | 39.44          | 34.522         | 37.323         | 0.081          | 45.59                       | 42.58          | 32.288         | 34.570         | 0.071          |
| 1962   | 51.87                       | 48.44          | 37.825         | 40.504         | 0.071          | 51.94                       | 50.91          | 37.774         | 38.539         | 0.020          |
| 2453   | 59.37                       | 55.38          | 41.317         | 44.294         | 0.072          | 60.55                       | 57.53          | 40.512         | 42.639         | 0.052          |

Figure 3-33: Experimental and computational flow resistances for all models with and without the arytenoid structure
Chapter 4

Results: Flow Visualizations

This chapter presents flow visualizations within the M6 model. The cases used to perform the visualizations are defined by the same experimental specifications as for the pressure and flow measurements. Similar to previous chapters, flow patterns for different glottal angles and diameters are discussed separately.

4.1 Introduction

Gross details of the flow pattern for each case were obtained using laser-sheet photography. The main focus of the resulting photos was on the flow within and a short distance downstream of the glottis. In this study, both coronal and sagittal views were obtained to investigate the three-dimensionality effects of the M6 model flow. The coronal and sagittal views of each glottis are presented on the same page in this chapter; different angles and diameters are discussed separately.

The flow visualizations were made for all the cases with and without the arytenoid cartilages structure at the three different planes for the coronal view and at the middle of the glottis for the sagittal view. Since the airflow seemed to be symmetric in the anterior-posterior direction for the cases without the arytenoid structure (due to non-eccentric configurations), in these cases the coronal views are presented only in...
the anterior (1/4) and middle planes, but for the cases with the arytenoid structure (eccentric configurations), three individual coronal planes are depicted. The two transglottal pressures 0.491 kPa (5 cm H₂O) and 1.472 kPa (15 cm H₂O) were used in the flow visualizations to cover essentially the whole range of phonation from soft to loud.

To investigate the flow patterns, some specifications need to be defined. Figure 4-1 shows all the parameters which were measured in this study. For all cases in the coronal and sagittal views, flow passing the glottis was laminar for a short distance. The length of the laminar core was defined in each coronal view as (L1) and in the sagittal views as (L2). Also in sagittal view, in all cases, the flow passing the glottis contracted toward the midcoronal plane. The contraction of the flow was specified with two parameters at the anterior and posterior ends. The widths of the approximate boundary layers at the anterior and posterior end are defined as W1 and W2, and their contraction angles defined as A1 and A2, respectively. In the cases where the photographs were not informative enough, the measurements of the flow specifications were obtained by using the movies which were taken during the flow visualizations.

4.2 Variable Glottal Angles

The results for the three glottal angles were compared with each other and will be discussed in this section. The flow visualizations are presented for glottal angles of 10° convergent (C16), 0° uniform (U16), and 10° divergent (D16). For all cases where glottal angle was varied, the minimal glottal diameter in the midcoronal plane was 0.16 cm. The flow visualizations for each case are presented on individual pages with coronal views at the beginning and the sagittal view last.
Figure 4-1: Schematic view of the parameters which defined in the glottal flow visualizations: a) Isometric view of the vocal folds, b) Coronal view (laminar core length defined as L1), and c) Sagittal view (laminar core length and contraction parameters defined as L2, W1, W2, A1, and A2, respectively).
4.2.1 Without arytenoid structure

4.2.1.1 Coronal plane

Figures 4-2a, 4-3a, and 4-4a show the flow patterns downstream of the glottis in the anterior (1/4) (or equivalently the posterior (3/4)) planes for the 10° convergent (C16), 0° uniform (U16), and 10° divergent (D16) cases, without the arytenoid cartilages structure, for a transglottal pressure of 0.491 kPa (5 cm H₂O), respectively. These figures show that the flow downstream of the vocal folds was laminar for a short distance. Vortex shedding and turbulence appeared further downstream from the glottal exit. Table 4.1 gives the flow parameters for the different glottal angles for a transglottal pressure of 0.491 kPa (5 cm H₂O). This table and corresponding figures show that the length of the laminar core (L1) is longer for the 10° divergent case (3.36 mm, real life) than for the 10° convergent case (2.52 mm), with the uniform case similar to the convergent case (2.52 mm).

Figures 4-2b, 4-3b, and 4-4b show that similar behavior occurred for the mid-coronal planes. The length of the laminar core in the midcoronal plane appears longer than in the anterior (1/4) plane in all the cases (see also Table 4.1) and was essentially doubled for the divergent case. The curvature of the glottis pushes the flow in the anterior-posterior direction toward the center line in the models with the half-sinusoidal arcs, and due to the symmetry of the flow, the secondary flows coming from anterior and posterior parts amplify each other in the midcoronal plane. That observation plus the fact of the larger diameter at the midcoronal section suggest that there will be a higher flow rate at this plane, and therefore the flow passing the glottis at the midcoronal plane will have higher momentum and a later transfer to turbulent flow.

Figures 4-5a, 4-6a, and 4-7a show the corresponding flow patterns for a transglottal pressure of 1.472 kPa (15 cm H₂O). Comparing these figures with the ones for
a transglottal pressure of 0.491 kPa (5 cm H₂O) show that the length of the laminar core decreased by 20-30% (average 26%) by increasing the transglottal pressure in the anterior (1/4) plane (see also Table 4.2). Figures 4-5b, 4-6b, and 4-7b suggest that the length of the laminar core was longer in the midcoronal plane rather than the anterior (1/4) plane even in the higher transglottal pressure (ranged from 20% to 50%, average of 36%).

4.2.1.2 Sagittal plane

Figures 4-2c, 4-3c, and 4-4c show the flow patterns downstream for the 10° convergent (C16), 0° uniform (U16), and 10° divergent (D16) cases, without the arytenoid cartilages structure, at a transglottal pressure of 0.491 kPa (5 cm H₂O), in the mid-sagittal plane, respectively. For all cases shown, the flow contracted toward the coronal center plane of the glottis after passing the vocal folds, changing from laminar to turbulent flow, and developing vortices, with expanding flows and induced wall effects on the flow patterns downstream of the glottis. The contraction of the flow (due to significant secondary flows) was not observed in the results of the M5 model with two-dimensional glottal shapes, and thus is caused here by the three-dimensionality of the glottis (see below for velocity profiles results).

In a rectangular glottis the flow is two-dimensional, so that velocities have significant components in the coronal cross-sections only, and the flow is analyzed in the x-y plane. The axial velocity (i.e., x-velocity) is the main velocity component, corresponding physiologically to the upward (subglottal-to-supraglottal) direction. The M6 glottis is half-sinusoidal on each side, and the anterior-posterior component of the velocity (z-velocity) cannot be neglected. This component is responsible for secondary flows in the three-dimensional glottis.

Since these cases had the non-eccentric geometries, the contraction angles and boundary layer thicknesses at the glottis exit in the anterior and posterior ends were
Table 4.1: Specifications of the flow visualizations for the cases with different glottal angles without the arytenoid structure for a transglottal pressure of 0.491 kPa (5 cm H$_2$O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

<table>
<thead>
<tr>
<th>Case</th>
<th>L1 (Ant)</th>
<th>L1 (Mid)</th>
<th>L2</th>
<th>W1</th>
<th>W2</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>C16</td>
<td>2.52</td>
<td>3.36</td>
<td>6.86</td>
<td>1.29</td>
<td>1.29</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>U16</td>
<td>2.52</td>
<td>4.20</td>
<td>7.71</td>
<td>1.71</td>
<td>1.71</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>D16</td>
<td>3.36</td>
<td>6.72</td>
<td>8.57</td>
<td>2.57</td>
<td>2.57</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

Identical (W1=W2 and A1=A2 in Tables 4.1 and 4.2). These figures and the corresponding tables also show that by changing the glottal angle from 10° divergent to 10° convergent, the length of the laminar core in the sagittal views (L2) and boundary layer thicknesses (W1 and W2) decreased, but (not surprisingly) the contraction angles of the flow increased (A1 and A2).

Figures 4-5c, 4-6c, and 4-7c show the flow patterns downstream for 10° convergent (C16), 0° uniform (U16), and 10° divergent (D16) cases at a transglottal pressure of 1.472 kPa (15 cm H$_2$O), in the midsagittal plane, respectively. Comparing these figures to the corresponding figures for a transglottal pressure of 0.491 kPa (5 cm H$_2$O) show that the laminar core (both L1 and L2) decreased by increasing the transglottal pressure, and thus vortex structure in the sagittal plane developed closer to the glottis. Because in the higher transglottal pressure the boundary layer grew slower, the values of W1, W2, and the contraction angle became smaller for the transglottal pressure of 1.472 kPa (15 cm H$_2$O). The change from 0.491 kPa (5 cm H$_2$O) to 1.472 kPa (15 cm H$_2$O) decreased the contraction angle by about 5° (10° for the included angle) for each glottal angle, changing the range from 17° - 30° to 12° - 25°.
Figure 4-2: Glottal flow visualization for the convergent case (C16), without the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.
Figure 4-3: Glottal flow visualization for the uniform case (diameter of 0.16 cm, U16), without the arytenoid structure, for $\Delta p_T=0.491$ kPa ($5\text{ cm H}_2\text{O}$): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.
Figure 4-4: Glottal flow visualization for the divergent case (D16), without the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.
Figure 4-5: Glottal flow visualization for the convergent case (C16), without the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.
Figure 4-6: Glottal flow visualization for the uniform case (diameter of 0.16 cm, U16), without the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.
Figure 4-7: Glottal flow visualization for the divergent case (D16), without the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.
Table 4.2: Specifications of the flow visualizations for the cases with different glottal angles without the arytenoid structure for a transglottal pressure of 1.472 kPa (15 cm H₂O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

<table>
<thead>
<tr>
<th>Case</th>
<th>L1 (Ant)</th>
<th>L1 (Mid)</th>
<th>L2</th>
<th>W1</th>
<th>W2</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>C16</td>
<td>2.02</td>
<td>2.52</td>
<td>6.00</td>
<td>1.03</td>
<td>1.03</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>U16</td>
<td>1.68</td>
<td>3.36</td>
<td>6.86</td>
<td>1.29</td>
<td>1.29</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>D16</td>
<td>2.52</td>
<td>4.20</td>
<td>7.71</td>
<td>2.14</td>
<td>2.14</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

4.2.2 With arytenoid structure

4.2.2.1 Coronal plane

Figures 4-8a, 4-9a, and 4-10a show the flow patterns downstream of the glottis in the anterior (1/4) planes for 10° convergent (C16), 0° uniform (U16), and 10° divergent (D16) cases, respectively, with the arytenoid cartilages structure, for a transglottal pressure of 0.491 kPa (5 cm H₂O). Comparing these figures with the figures for the posterior (3/4) planes (see Fig. 4-8c, 4-9c, and 4-10c) does not show any obvious differences in the flow patterns between the anterior (1/4) and posterior (3/4) planes (see also Table 4.3 where the laminar core measures are reported to be the same for both). Similar to the cases without the arytenoid cartilages structure, the length of the laminar core decreased by changing the glottal angle from 10° divergent to 10° convergent in all three coronal planes. Figures 4-8b, 4-9b, and 4-10b show again that the length of the laminar core in the midcoronal plane was longer than for the other two planes.

Figures 4-11 (a,b,c), 4-12 (a,b,c), and 4-13 (a,b,c) show the corresponding flow patterns for a transglottal pressure of 1.472 kPa (15 cm H₂O). Comparing these figures with the ones for a transglottal pressure of 0.491 kPa (5 cm H₂O) indicate that the flow patterns do not significantly change by increasing the transglottal pressure except that the length of the laminar core is decreased by increasing the transglottal pressure.
pressure (see Table 4.4) within the range of 10% to 28% (average of 21%).

Therefore, there was (surprisingly) little to no effect on the axial laminar core lengths at the three coronal planes due to the presence of the arytenoid structure, in contrast to significant changes in the flow within the sagittal plane (discussed next).

4.2.2.2 Sagittal plane

Figures 4-8d, 4-9d, and 4-10d show the flow patterns downstream for the 10° convergent (C16), 0° uniform (U16), and 10° divergent (D16) cases, respectively, with the arytenoid cartilages structure for a transglottal pressure of 0.491 kPa (5 cm H₂O), in the midsagittal plane. Similar to the cases without the arytenoid cartilages structure, the flow contracted toward the coronal center plane after passing the vocal folds. The differences between the flow patterns of the eccentric and non-eccentric geometries are in the contraction parameters. The angles A1 and A2 of the contraction in the non-eccentric cases (see Section 4.2.1.2) were essentially the same at the anterior and posterior locations (end commissures), but in the eccentric cases, the contraction angle A1 for the anterior location was smaller than A2 at the posterior location by 3° - 5°. For instance, for the 10° divergent case, the anterior contraction angle was 30° compared to 35° for the posterior contraction angle (Table 4.3). It is speculated that this occurred due to flow circulation in the concavity inferior to the arytenoid cartilages structure pushing the flow in the posterior to anterior direction and causing a higher flow bend at the posterior location than at the anterior location (which will be shown numerically below, see Chapter 5). This phenomenon not only changed the contraction angles, but also changed the boundary layer thicknesses at the anterior and posterior ends. As Table 4.3 shows, in all three cases, the boundary layer thickness W2 at the posterior end was 2 to 2.5 times greater than W1 at the anterior end. Similar to the non-eccentric cases, these figures also show that by changing the glottal angle from 10° divergent to 10° convergent, the length L2 of the laminar core
decreased from 7.7 mm to 6.4 mm and the boundary layer thickness W1 and W2 decreased by a factor of 2. It is noteworthy that the eccentricity did not affect the boundary layer W1 value at the anterior end but did shorter the laminar core L2 by about 9%.

Figures 4-11d, 4-12d, and 4-13d show the corresponding flow patterns, for the higher transglottal pressure of 1.472 kPa (15 cm H₂O). Comparing these figures to the corresponding figures for a transglottal pressure of 0.491 kPa (5 cm H₂O) shows that the angle of the contraction in both locations (anterior and posterior ends) decreased by 2° - 3° by increasing the transglottal pressure. Similar to the non-eccentric cases, the laminar core (both L1 and L2), the boundary layer thicknesses (W1 and W2), and the contraction angles decreased by increasing the transglottal pressure as shown in Table 4.4. The sagittal figures for both transglottal pressures show that the flow passing the glottis did not appear to be affected by the superior curvature of the arytenoid cartilages structure. In the fluid mechanics perspective, the flow did not “see” the arytenoid curvature and passed by it without being affected. Therefore, it can be assumed that just the eccentricity of the glottis and the slight concavity of the inferior arytenoid cartilages structure played a role in affecting the intraglottal and supraglottal aerodynamics.

Thus, in general, the eccentricity altered the midsagittal contraction flow exiting the glottis by (a) reducing the laminar core length, (b) increasing the boundary layer thickness at the posterior glottal exit, and (c) increasing the contraction at the posterior end. In addition, in general, for the midsagittal contraction flow, with or without the eccentricity, the divergent glottis created (a) the longest laminar core lengths, (b) the largest boundary layer values, and (c) the largest contraction angles, where the convergent glottis created the least values for these parameters, and the uniform glottis intermediate values. Also, increasing transglottal pressure shortened all laminar core lengths, decreased all boundary layer values and reduced all contraction angles.
Table 4.3: Specifications of the flow visualizations for the cases with different glottal angles with the arytenoid structure for a transglottal pressure of 0.491 kPa (5 cm H₂O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

<table>
<thead>
<tr>
<th>Case</th>
<th>L1 (Ant)</th>
<th>L1 (Mid)</th>
<th>L1 (Pos)</th>
<th>L2</th>
<th>W1</th>
<th>W2</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>C16</td>
<td>2.52</td>
<td>3.36</td>
<td>2.52</td>
<td>6.43</td>
<td>1.29</td>
<td>2.57</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>U16</td>
<td>2.52</td>
<td>3.70</td>
<td>2.52</td>
<td>6.86</td>
<td>1.71</td>
<td>4.29</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>D16</td>
<td>3.36</td>
<td>5.88</td>
<td>3.36</td>
<td>7.71</td>
<td>2.57</td>
<td>6.00</td>
<td>30</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 4.4: Specifications of the flow visualizations for the cases with different glottal angles with the arytenoid structure for a transglottal pressure of 1.472 kPa (15 cm H₂O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

<table>
<thead>
<tr>
<th>Case</th>
<th>L1 (Ant)</th>
<th>L1 (Mid)</th>
<th>L1 (Pos)</th>
<th>L2</th>
<th>W1</th>
<th>W2</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>C16</td>
<td>2.02</td>
<td>2.52</td>
<td>2.02</td>
<td>6.00</td>
<td>1.03</td>
<td>2.23</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>U16</td>
<td>1.68</td>
<td>3.36</td>
<td>1.68</td>
<td>6.00</td>
<td>1.46</td>
<td>3.86</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>D16</td>
<td>2.52</td>
<td>4.20</td>
<td>2.52</td>
<td>7.29</td>
<td>2.14</td>
<td>5.14</td>
<td>27</td>
<td>33</td>
</tr>
</tbody>
</table>
Figure 4-8: Glottal flow visualization for the convergent case (C16), with the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal.
Figure 4-9: Glottal flow visualization for the uniform case (diameter of 0.16 cm, U16), with the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal.
Figure 4-10: Glottal flow visualization for the divergent case (D16), with the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal.
Figure 4-11: Glottal flow visualization for the convergent case (C16), with the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior ($1/4$)-coronal, b) Mid-coronal, c) Posterior ($3/4$)-coronal, and d) Mid-sagittal.
Figure 4-12: Glottal flow visualization for the uniform case (diameter of 0.16 cm, U16), with the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal.
Figure 4-13: Glottal flow visualization for the divergent case (D16), with the arytenoid structure, for $\Delta p_T = 1.472$ kPa ($15$ cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal.
4.3 Variable Glottal Diameters

In this section, the cases with different glottal diameters are presented. The chosen glottal diameters were 0.16 cm (U16), 0.04 cm (U04), and 0.01 cm (U01). For each case, the glottal shape was uniform (a glottal angle of $0^\circ$). The uniform case with glottal diameter of 0.16 cm (U16), was discussed in sections 4.2.1 and 4.2.2; it will be compared with other cases in this section. The glottal diameter effects were studied for two different conditions, with and without the arytenoid structure for two transglottal pressures. The flow visualizations for each case are presented on individual page with coronal views at the beginning and the sagittal view last.

4.3.1 Without arytenoid structure

4.3.1.1 Coronal plane

Figures 4-3a, 4-14a, and 4-15a show the flow patterns downstream of the glottis in the anterior (1/4) (or equivalently the posterior (3/4)) planes for the $0^\circ$ uniform cases with diameters of 0.16 cm (U16), 0.04 cm (U04), and 0.01 cm (U01), respectively, without the arytenoid cartilages structure, for a transglottal pressure of 0.491 kPa (5 cm H$_2$O). The length of the laminar core increased by 31-50% by increasing the glottal diameter (see also Table 4.5). By decreasing the diameter of the glottis, the aspect ratio of the anterior-posterior length to midcoronal diameter increased. This appears to be reflected in the skewing of the glottal jet for a diameter of 0.01 cm (U01) where the exit flow moved toward one wall of the downstream tunnel (Fig. 4-15a). This skewness follows the trend observed with rectangular glottal shapes [37, 38, 40]. This skewness was also produced in the numerical runs by imposing a small downstream cross-channel pressure gradient (0.0 - 0.2 Pa) as a boundary condition (see Chapter 5). Figures 4-3b, 4-14b, and 4-15b show that the same behavior occurred in the midcoronal planes. The length of the laminar core in the midcoronal plane
increased by 7-25% with increase in diameter, and was higher than in the two other planes by a factor of 1.67 to 2.0 (Table 4.5). The skewness angle in the anterior (1/4) plane was 55° away from the midsagittal axial plane, which was higher than the skewness angle of the midcoronal plane (50°).

Figures 4-6(a,b), 4-16(a,b), and 4-17(a,b) show the corresponding flow patterns for a transglottal pressure of 1.472 kPa (15 cm H₂O). Comparing these figures with the ones for a transglottal of 0.491 kPa (5 cm H₂O) indicate that the skewness angle of the flow in the uniform case with the smallest diameter decreased (i.e., the flow inclined more toward the center) by increasing the transglottal pressure. The skewness angles in the anterior (1/4) and midcoronal planes for a transglottal pressure of 1.472 kPa (15 cm H₂O) were 35° and 30°, respectively. Similar to the cases with different glottal angles, the length of the laminar core decreased (by 14-33%) for all the cases by increasing the transglottal pressure, again with longer laminar core lengths for greater diameter values (see Table 4.6).

4.3.1.2 Sagittal plane

Figures 4-3c, 4-14c, and 4-15c show the flow patterns downstream for the 0° uniform cases with diameters of 0.16 cm (U16), 0.04 cm (U04), and 0.01 cm (U01), respectively, without the arytenoid cartilages structure, for a transglottal pressure of 0.491 kPa (5 cm H₂O) in the midsagittal plane. By increasing the glottal diameter, the contraction angles (A1 and A2) decreased by 13° and the boundary layer thickness in both anterior and posterior ends (W1 and W2) decreased by a factor of 2 (see Table 4.5). Also, the length L2 of the laminar core increased by a factor of 3 by increasing the glottal diameter. It is noted that for the uniform case with the smallest glottal diameter (Fig. 4-15c), due to the low rate of flow and gravity forces, smoke did not fill all of the wind tunnel cross section and moved toward the floor of the tunnel. This limited the visualization in the sagittal plane.
Table 4.5: Specifications of the flow visualizations for the cases with different glottal diameters without the arytenoid structure for a transglottal pressure of 0.491 kPa (5 cm H\textsubscript{2}O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

<table>
<thead>
<tr>
<th>Case</th>
<th>L1 (Ant)</th>
<th>L1 (Mid)</th>
<th>L2</th>
<th>W1</th>
<th>W2</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>U16</td>
<td>2.52</td>
<td>4.20</td>
<td>7.71</td>
<td>1.71</td>
<td>1.71</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>U04</td>
<td>2.20</td>
<td>3.60</td>
<td>4.29</td>
<td>2.14</td>
<td>2.14</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>U01</td>
<td>1.68</td>
<td>3.36</td>
<td>2.57</td>
<td>3.43</td>
<td>3.43</td>
<td>35</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 4.6: Specifications of the flow visualizations for the cases with different glottal diameters without the arytenoid structure for a transglottal pressure of 1.472 kPa (15 cm H\textsubscript{2}O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

<table>
<thead>
<tr>
<th>Case</th>
<th>L1 (Ant)</th>
<th>L1 (Mid)</th>
<th>L2</th>
<th>W1</th>
<th>W2</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>U16</td>
<td>1.68</td>
<td>3.36</td>
<td>6.86</td>
<td>1.29</td>
<td>1.29</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>U04</td>
<td>1.52</td>
<td>3.10</td>
<td>3.43</td>
<td>1.71</td>
<td>1.71</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>U01</td>
<td>1.26</td>
<td>2.52</td>
<td>2.14</td>
<td>3.00</td>
<td>3.00</td>
<td>32</td>
<td>32</td>
</tr>
</tbody>
</table>

Figures 4-6c, 4-16c, and 4-17c show the flow patterns downstream for the 0° uniform cases with diameters of 0.16 cm (U16), 0.04 cm (U04), and 0.01 cm (U01), respectively, for a transglottal pressure of 1.472 kPa (15 cm H\textsubscript{2}O), in the midsagittal plane. Comparing these figures to the corresponding figures for a transglottal pressure of 0.491 kPa (5 cm H\textsubscript{2}O) show that, by increasing the transglottal pressure, the laminar core L2 decreased by 11-20% and the boundary layer thicknesses (W1 and W2) decreased by 13-25%. The contraction angles decreased by 2° - 4° by increasing the transglottal pressure (see Table 4.6).
Figure 4-14: Glottal flow visualization for the uniform case (diameter of 0.04 cm, U04), without the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.
Figure 4-15: Glottal flow visualization for the uniform case (diameter of 0.01 cm, U01), without the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.
Figure 4-16: Glottal flow visualization for the uniform case (diameter of 0.04 cm, U04), without the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.
Figure 4-17: Glottal flow visualization for the uniform case (diameter of 0.01 cm, U01), without the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, and c) Mid-sagittal.
4.3.2 With arytenoid structure

4.3.2.1 Coronal plane

Figures 4-9a, 4-18a, and 4-19a show the flow patterns downstream of the glottis in the anterior (1/4) plane for the 0° uniform cases with diameters of 0.16 cm (U16), 0.04 cm (U04), and 0.01 cm (U01), respectively, with the arytenoid cartilages structure for a transglottal pressure of 0.491 kPa (5 cm H₂O). Comparing these figures with the figures for the posterior (3/4) planes (see Fig. 4-9c, 4-18c, and 4-19c) show that, similar to the eccentric cases for different glottal angles with the glottal diameter of 0.16 cm (see Section 4.2.2.1), the coronal flow patterns do not significantly or consistently change and they are almost symmetric (Table 4.7). Again, the coronal laminar core lengths appear to be insensitive to the presence of the eccentricity. Similar to the non-eccentric cases, the length of the laminar core in the eccentric cases increased by increasing the glottal diameter. Figures 4-9b, 4-18b, and 4-19b show that the same behavior occurred in the midcoronal planes. The length of the laminar core in the midcoronal plane was higher than for the other two planes.

Figures 4-12(a,b,c), 4-20(a,b,c), and 4-21(a,b,c) show the corresponding flow patterns for a transglottal pressure of 1.472 kPa (15 cm H₂O). Comparing these figures with the ones for a transglottal pressure of 0.491 kPa (5 cm H₂O) show that, similar to the non-eccentric cases, the skewness angle of the flow in the uniform case with the smallest diameter decreased by increasing the transglottal pressure (from 50° to 30° for the midcoronal plane and from 55° to 35° for the anterior and posterior planes) and the length of the laminar core decreased for all cases by increasing the transglottal pressure (see also Table 4.8).
4.3.2.2 Sagittal plane

Figures 4-9d, 4-18d, and 4-19d show the flow patterns downstream for the 0° uniform cases with diameters of 0.16 cm (U16), 0.04 cm (U04), and 0.01 cm (U01), respectively, with the arytenoid cartilages structure for a transglottal pressure of 0.491 kPa (5 cm H₂O), in the midsagittal plane. The effects of eccentricity here are quite similar to those for the various glottal angles and diameter of 0.16 cm (see Section 4.2.2.2), except for a significantly weaker effect on the W2 for the smaller diameter cases, U01 and U04, where the increase in W2 was only 5% for U01 and 8% for U04, whereas the increases for the angle series was a factor of 2-2.5, and here a factor of 2.5 again for U16. It is speculated that the effects of the arytenoid structure decreased due to lower flow rates in the lower glottal diameter cases (see Chapter 5). The angle of the contraction in the posterior location was 3° greater than at the anterior location. These figures also show that the length of the laminar core decreased by decreasing the glottal diameter (see Table 4.7).

Figures 4-12d, 4-20d, and 4-21d show the flow patterns downstream for the 0° uniform cases with diameters of 0.16 cm (U16), 0.04 cm (U04), and 0.01 cm (U01), respectively, with the arytenoid cartilages structure for a transglottal pressure of 1.472 kPa (15 cm H₂O), in the midsagittal plane. Comparing these figures to the corresponding figures for a transglottal pressure of 0.491 kPa (5 cm H₂O) show that similar to the non-eccentric cases, the contraction angles at the anterior and posterior locations decreased by 1° - 3° by increasing the transglottal pressure, and the laminar core L2 decreased by 13 - 20% (see Table 4.8). In general, the presence or absence of the arytenoid structure did not have any major effect on the flow patterns for the cases with lower diameters (U01, and U04).

Thus, in general, the eccentricity for the diameter series altered the midsagittal contraction flow exiting the glottis by (a) reducing the laminar core length, (b) increasing the boundary layer thickness at the posterior end but less for smaller diameters,
Table 4.7: Specifications of the flow visualizations for the cases with different glottal diameters with the arytenoid structure for a transglottal pressure of 0.491 kPa (5 cm H$_2$O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

<table>
<thead>
<tr>
<th>Case</th>
<th>L1 (Ant)</th>
<th>L1 (Mid)</th>
<th>L1 (Pos)</th>
<th>L2</th>
<th>W1</th>
<th>W2</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>U16</td>
<td>2.52</td>
<td>3.70</td>
<td>2.52</td>
<td>6.86</td>
<td>1.71</td>
<td>4.29</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>U04</td>
<td>2.20</td>
<td>3.60</td>
<td>2.20</td>
<td>3.43</td>
<td>2.14</td>
<td>2.31</td>
<td>25</td>
<td>28</td>
</tr>
<tr>
<td>U01</td>
<td>1.68</td>
<td>3.40</td>
<td>1.68</td>
<td>2.14</td>
<td>3.43</td>
<td>3.60</td>
<td>35</td>
<td>38</td>
</tr>
</tbody>
</table>

Table 4.8: Specifications of the flow visualizations for the cases with different glottal diameters with the arytenoid structure for a transglottal pressure of 1.472 kPa (15 cm H$_2$O). All lengths are in mm (real life) and angles are in degree (see Fig. 4-1).

<table>
<thead>
<tr>
<th>Case</th>
<th>L1 (Ant)</th>
<th>L1 (Mid)</th>
<th>L1 (Pos)</th>
<th>L2</th>
<th>W1</th>
<th>W2</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>U16</td>
<td>1.68</td>
<td>3.36</td>
<td>1.68</td>
<td>6.00</td>
<td>1.46</td>
<td>3.86</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>U04</td>
<td>1.52</td>
<td>3.10</td>
<td>1.52</td>
<td>3.00</td>
<td>1.89</td>
<td>2.14</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>U01</td>
<td>1.26</td>
<td>2.52</td>
<td>1.26</td>
<td>1.71</td>
<td>3.00</td>
<td>3.43</td>
<td>33</td>
<td>36</td>
</tr>
</tbody>
</table>

and (c) increasing the contraction angle at the posterior end. In addition, in general for the midsagittal contraction flow, with or without eccentricity, larger diameters create (a) larger laminar core lengths, (b) smaller anterior boundary layers, (c) mixed posterior boundary layers (with eccentricity, U16 had the largest posterior boundary layer thickness, U04 the least), and (d) the smallest contraction angles. Also, increasing transglottal pressure shortened all laminar core lengths, decreased all boundary layer thicknesses, and reduced all contraction angles.
Figure 4-18: Glottal flow visualization for the uniform case (diameter of 0.04 cm, U04), with the arytenoid structure, for $\Delta p_T = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal.
Figure 4-19: Glottal flow visualization for the uniform case (diameter of 0.01 cm, U01), with the arytenoid structure, for $\Delta p = 0.491$ kPa (5 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal.
Figure 4-20: Glottal flow visualization for the uniform case (diameter of 0.04 cm, U04), with the arytenoid structure, for $\Delta p_T = 1.472$ kPa (15 cm H$_2$O): a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal.
Figure 4-21: Glottal flow visualization for the uniform case (diameter of 0.01 cm, U01), with the arytenoid structure, for $\Delta p_T = 1.472 \text{ kPa (15 cm H}_2\text{O)}$: a) Anterior (1/4)-coronal, b) Mid-coronal, c) Posterior (3/4)-coronal, and d) Mid-sagittal.
The findings of the flow visualizations can be summarized as follows:

(a) The airflow passing the glottis was laminar for a short distance.

(b) The length of the laminar core was higher in the midcoronal plane than the anterior (1/4) and posterior (3/4) planes. It decreased by changing the glottal angle from the 10° divergent case to the 10° convergent case and it also decreased by decreasing the glottal diameter.

(c) Increasing transglottal pressure decreased the laminar core length.

(d) Flow patterns in the coronal views did not change appreciably comparing the non-eccentric and eccentric cases.

(e) In the sagittal view, for all cases, the flow contracted toward the midcoronal plane with a fast growing boundary layer starting at the glottal entrance and also with a short laminar core length.

(f) Similar to the coronal view, the length of the laminar core in the sagittal view decreased by changing the glottal angle from the 10° divergent case to the 10° convergent case and it decreased by decreasing the glottal diameter.

(g) In the sagittal view, by increasing the transglottal pressure, the contraction angles and the laminar core decreased.

(h) The thickness of the boundary layer was similar at the anterior and posterior ends for the non-eccentric cases. For the eccentric cases, the anterior thickness was smaller than the posterior thickness due to the flow bending.

(i) By increasing the transglottal pressure, the boundary layer thicknesses decreased in all cases at both the anterior and posterior ends.

(j) Only for the case with the smallest glottal diameter (U01) did the flow skew (due to the high aspect ratio of the glottis, small diameter, and low flow). The skewness angle was higher at the anterior (1/4) and posterior (3/4) planes than at the midcoronal plane.

(k) Increasing transglottal pressure decreased the skewness angle of the flow.
Chapter 5

Results: FLUENT Computations

In this chapter, empirical pressure distributions and flow visualizations are discussed relative to corresponding pressure fields and velocity profiles from FLUENT. The same sequence as in previous chapters will be followed for different glottal angles and diameters, with and without the arytenoid cartilages structure.

5.1 Introduction

Figure 5-1 illustrates the structured mesh used in FLUENT for the M6 model at the mid-coronal plane for the uniform glottis. The glottis has been enlarged to show the cross-channel flow details (the pressure contours and velocity profiles) in the following figures for different cases. The transglottal pressure of 0.981 kPa (10 cm H$_2$O) is a pressure commonly used in phonation studies, and therefore will be used here.

The flow details were obtained for all the cases with and without the arytenoid cartilages structure at the three different planes for the coronal view and at the middle of the glottis for the sagittal view. For non-eccentric cases, the coronal views are presented only in the anterior (1/4) and middle planes, but for the eccentric cases, the three individual coronal planes will be shown.

The pressure contours for each case are followed by the corresponding velocity
Figure 5-1: Schematic view of mesh in mid-coronal plane for the M6 model for the uniform glottis. Section A-A indicates the mid-sagittal plane out of the page.

profiles in the different coronal planes to give comprehensive information within the glottis. In the sagittal view, both streamlines and velocity contours are presented. For the sake of clarity and comparability in the sagittal view, the velocity contours are only shown within the glottis side by side for non-eccentric and eccentric geometries. Streamlines are presented in the whole domain. Also, to compare more directly with the non-eccentric cases, the domain for the eccentric cases will be restricted to the same regions used for the non-eccentric cases. For the cases with different diameters, the scale of the y-axis was adjusted to see details better.
5.2 Variable Glottal Angles

The three different glottal angles were compared with each other and will be discussed in this section. The flow details are presented for the glottal angles of 10° convergent (C16), 0° uniform (U16), and 10° divergent (D16). For all cases where glottal angle was varied, the minimal glottal diameter in the midcoronal plane was 0.16 cm.

5.2.1 Without arytenoid structure

5.2.1.1 Coronal plane

Figures 5-2(a,b) show the pressure contours within the glottis for the 10° convergent case (C16) in the anterior (1/4) (or equivalently posterior (3/4)) and the midcoronal planes, respectively, without the arytenoid cartilages structure. Both Fig. 3-6 and Fig. 5-2 indicate that, although the intraglottal pressures at the two planes were different at the glottal entrance, they were nearly the same at the glottal exit. There was an abrupt gradient change in the pressure field along the inferior vocal fold surface near the glottal entrance which was not a separation point. The pressure values within the glottis decreased axially, and therefore the adverse pressure gradient (increasing pressure) which is an essential condition for flow separation was not created until the point that the glottal exit curvature began and the cross-sectional area of the glottis increased. The separation point occurred near the location with the smallest glottal diameter at the axial location of 2.15 mm for the midcoronal plane and just slightly upstream at 2.12 mm for the anterior (1/4) plane (see Fig. 5-2(a,b)). Therefore, the locations of the separation points at the anterior (1/4) and midcoronal planes were slightly different axially. For a short distance downstream of the entrance and before the separation points, the pressures became nearly constant perpendicular to the walls in both planes.
Figure 5-2: Pressure contours at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for convergent glottis (C16): a) Anterior (1/4)-coronal, and b) Middle-coronal. Values of the contours are in kPa.
Figure 5-3: Coronal velocity profiles within the glottis at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for convergent glottis (C16): a) Anterior (1/4)-coronal, and b) Middle-coronal.
Figures 5-3(a,b) show the velocity profiles within the glottis for the 10° convergent case (C16) in the anterior (1/4) (or equivalently posterior (3/4)) and the midcoronal planes, respectively, without the arytenoid cartilages structure. These figures show the contraction of the flow within the glottis along the inferior to superior direction up to the smallest glottal diameter. The reference vector in each graph provides a way to estimate the velocity values in each section. The small vectors near the walls at the section close to the glottal exit indicate separation of the flow.

Figures 5-4(a,b) and Fig. 5-5(a,b) show the pressure contours and velocity profiles within the glottis for the 0° uniform case with diameter of 0.16 cm (U16) in the anterior (1/4) (or equivalently posterior (3/4)) and the midcoronal planes, respectively, without the arytenoid cartilages structure. These figures show that, although the intraglottal pressures were similar at the glottal entrance and exit in both planes, between those two locations the wider glottal diameter plane (midcoronal plane) had the higher intraglottal pressure axially (as seen in Fig. 3-6). For this case, there were two adverse pressure gradients, the first one near the glottal entrance and the second one which occurred near the glottal exit where the glottal exit curvature began. The flow separations started at axial location of 2.08 mm for the midcoronal plane and 2.05 mm for the anterior (1/4) plane (see Fig. 5-4(a,b)). Similar to the convergent case, the axial locations of the flow separation at the anterior (1/4) and the midcoronal planes were slightly different axially. Contrary to the 10° convergent case, in this case the pressures were not constant perpendicular to the walls at locations between the glottal entrance and exit. The velocity profiles of Fig. 5-5, show that the flow was developing within the glottis duct from glottal entrance to exit, but the flow separated farther downstream in the convergent case compared to the uniform case (with the reminder that the exit radius was smaller for the convergent glottis).

Figures 5-6(a,b), and Fig. 5-7(a,b) show the pressure contours and velocity profiles within the glottis for the 10° divergent case (D16) in the anterior (1/4) (or equiva-
Figure 5-4: Pressure contours at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa ($10$ cm H₂O), for uniform glottis with diameter of $0.16$ cm (U16): a) Anterior ($1/4$)-coronal, and b) Middle-coronal. Values of the contours are in kPa.
Figure 5-5: Coronal velocity profiles within the glottis at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.16 cm (U16): 
a) Anterior (1/4)-coronal, and b) Middle-coronal.
lently posterior (3/4)) and the midcoronal planes, respectively, without the arytenoid cartilages structure. These figures indicate that, although the intraglottal pressures were different at the glottal entrance in the anterior (1/4) and midcoronal planes, they were close to each other within the glottis (as seen in Fig. 3-6). Contrary to the 10° convergent and 0° uniform cases, in this case the adverse pressure gradient began at the glottal entrance and remained throughout the entire glottis which made the boundary layer grow faster than for the other two cases. The flow separations started at axial location of -0.05 mm for the midcoronal plane and -0.02 mm for the anterior (1/4) plane, just upstream of the glottal entrance proper (see Fig. 5-6(a,b)). It is noted that for the 10° convergent and 0° uniform cases, the separation point at the midcoronal plane occurred slightly further downstream than at the anterior (1/4) plane, but for the 10° divergent case, it occurred slightly upstream in the midcoronal plane. Similar to the 0° uniform case, in this case the pressures were not constant perpendicular to the walls between the glottal entrance and exit.

5.2.1.2 Sagittal plane

Flow visualization figures indicate that because of the half-sinusoidal shaping of the glottis, there was creation of flow from the anterior and posterior ends toward the center of the glottal duct, as well as a contracting jet downstream of the glottis. Figures 5-8(a,b,c) show the flow streamlines in the mid-sagittal plane for the 10° convergent case (C16), 0° uniform case (U16), and 10° divergent case (D16), respectively, all with diameter of 0.16 cm, without the arytenoid cartilages structure. In the 10° convergent case, the flow separation at the narrow anterior-posterior ends of the glottis in the sagittal plane occurred near the glottal exit (as it did in the coronal plane), and in the 10° divergent case, the flow separation occurred at the two ends near the entrance of the glottis in the sagittal plane (as it did in the coronal plane). It is noted that the separation points began at the anterior and posterior ends up-
Figure 5-6: Pressure contours at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for divergent glottis (D16): a) Anterior (1/4)-coronal, and b) Middle-coronal. Values of the contours are in kPa.
Figure 5-7: Coronal velocity profiles within the glottis at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for divergent glottis (D16): a) Anterior (1/4)-coronal, and b) Middle-coronal.
stream of the glottal exit for all three cases, and that the secondary cross flow effect relative to extension toward the center of the glottis was greatest for the divergent angle (also see Fig. 5-17a to Fig. 5-19a). Thus, the faster-growing viscous boundary layer at the anterior and posterior ends for the $10^\circ$ divergent case created greater three-dimensionality effects of the flow.

The boundary layer thickness at the glottal exit was 18% of the anterior-posterior length for the divergent case and 8% for the convergent case. These boundary layer thicknesses can be seen in Fig. 5-17a to Fig. 5-19a, especially at the exit line where the flow was reversed and the flow exiting the glottis converged toward the mid-line. The large portion of the exit line in the divergent case with zero-length arrows shows the large thickness of the boundary layer and significant secondary flow.

5.2.2 With arytenoid structure

5.2.2.1 Coronal plane

Figures 5-9(a,b,c) show the pressure contours within the glottis for the $10^\circ$ convergent case (C16) in the anterior (1/4), midcoronal, and posterior (3/4) planes, respectively, with the arytenoid cartilages structure included in model M6. Both Fig. 3-15 and Fig. 5-9 indicate that the intraglottal pressures were different at the glottal entrance, more so than for the cases without the arytenoid structure. They were nearly the same at the glottal exit, however. The pressure values at the same axial location near the glottal entrance were highest for the anterior (1/4) plane, intermediate for the posterior (3/4) plane, and lowest for the midcoronal plane. The pressure difference between the pressures of middle and posterior (3/4) sections was 30 Pa, or 3% of the transglottal pressure, and between the posterior (3/4) and anterior (1/4) sections was 20 Pa, or 2%. The pressure values within the glottis decreased axially up to the point where the cross-sectional area of the glottis increased near the exit.
Figure 5-8: Flow streamlines in the mid-sagittal plane, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), with different glottal angles: a) convergent (C16), b) uniform glottis (U16), and c) divergent (D16). D=0.16 cm.
Figure 5-9: Pressure contours at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for convergent glottis (C16): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. Values of the contours are in kPa.
Axial distance \[10^{-3}\text{m}\]
Lateral distance \[10^{-3}\text{m}\]

Entrance
Exit

Reference vector: \[40\text{ (m/s)}\]

Figure 5-10: Coronal velocity profiles within the glottis at different coronal planes, with the arytenoid structure, for \(\Delta p_T = 0.981\text{ kPa (10 cm H}_2\text{O)}\), for convergent glottis (C16): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal.

142
Contrary to the corresponding case without the arytenoid structure, the separation points in all three planes occurred in nearly the same axial location of 2.15 mm (see Fig. 5-9(a,b,c)). Similar to the corresponding case without the arytenoid structure, for a short distance downstream of the entrance and before the separation points, the pressures became nearly constant perpendicular to the walls in both planes.

Figures 5-10(a,b,c) show the velocity profiles within the glottis for the 10° convergent case (C16) in the anterior (1/4), midcoronal, and posterior (3/4) planes, respectively, with the arytenoid cartilages structure. These figures show the same contraction of the flow within the glottis along the inferior to superior direction up to the smallest glottal diameter (as seen in the corresponding case without the arytenoid). Although the velocity profiles in these figures for the case with and without the arytenoid cartilages appear similar, flow visualizations and FLUENT results showed that in the presence of the arytenoid structure, additional posterior to anterior velocity component appeared in the midsagittal plane (see Section 5.2.2.2).

Figures 5-11(a,b,c), and Fig. 5-12(a,b,c) show the pressure contours and velocity profiles within the glottis for the 0° uniform case with diameter of 0.16 cm (U16) in the anterior (1/4), midcoronal, and posterior (3/4) planes, respectively, with the arytenoid cartilages structure. These figures show that, contrary to the corresponding case without the arytenoid, the intraglottal pressures were different for the three coronal planes at the glottal entrance (with the anterior location the lowest and posterior the highest). These values were zero for the middle plane, but 37 Pa (3.7%) for the posterior (3/4), and -33 Pa (3.4%) for the anterior (1/4) plane. Intraglottal pressures converged together at the glottal exit for all three planes; between the glottal entrance and exit, the anterior (1/4) plane had lower intraglottal pressure axially than the middle and the posterior (3/4) planes (as seen in Fig. 3-15). Similar to the corresponding case without the arytenoid, there were two adverse pressure gradients, one from tap #6 (glottal entrance) to tap #7, the second one where the
Figure 5-11: Pressure contours at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa ($10$ cm H$2$O), for uniform glottis with diameter of 0.16 cm (U16): a) Anterior ($1/4$)-coronal, b) Middle-coronal, and c) Posterior ($3/4$)-coronal. Values of the contours are in kPa.
Figure 5-12: Coronal velocity profiles within the glottis at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.16 cm (U16): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal.
glottal exit curvature began. Similar to the 10° convergent case with the arytenoid structure, in this case, the flow separation points in all three coronal plane occurred at the same axial location of 2.05 mm (see Fig. 5-11(a,b,c)). Contrary to the 10° convergent case, however, in this case the pressures were not constant perpendicular to the walls downstream of the flow between the glottal entrance and exit.

Figures 5-13(a,b,c), and Fig. 5-14(a,b,c) show the pressure contours and velocity profiles within the glottis for the 10° divergent case (D16) in the anterior (1/4), midcoronal, and posterior (3/4) planes, respectively, with the arytenoid cartilages structure. These figures show that, although the intraglottal pressures were identical at the glottal entrance in the anterior (1/4) and midcoronal planes, both of them were lower (by about 78 Pa or 8% of the transglottal pressure) than the intraglottal entrance pressure in the posterior (3/4) plane (as seen in Fig. 3-15). Similar to the corresponding case without the arytenoid, in this case the adverse pressure gradient began at the glottal entrance and it remained within the entire glottis which made the boundary layer grow faster than for the other two cases. Also, the flow separation points were axially identical at the location of -0.05 mm for all three coronal planes (see Fig. 5-13(a,b,c)). In this case, the pressures were not constant perpendicular to the walls downstream of the flow between the glottal entrance and exit.

5.2.2.2 Sagittal plane

Figures 5-15(a,b,c) show the flow streamlines in the mid-sagittal plane for the 10° convergent case (C16), 0° uniform case (U16), and 10° divergent case (D16), respectively, all with diameter of 0.16 cm and with the arytenoid cartilages structure. The blank area in the figures is the location of the arytenoid cartilages structure. As these figures show, the flow patterns were not symmetric in the posterior-anterior direction. Due to the presence of the arytenoid cartilages structure, the flow patterns became three-dimensional. Beneath the arytenoid structure near the plane of the
Figure 5-13: Pressure contours at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for divergent glottis (D16): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. Values of the contours are in kPa.
Figure 5-14: Coronal velocity profiles within the glottis at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for divergent glottis (D16): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal.
glottal entrance, there were some spot-emanations of the flow which indicated the primarily anteriorly directed airflow in this area. This flow occurred due to the shape of the arytenoid structure (as shown in Fig. 2-2) and to the incoming flow that was subjected to the lateral forces because of the inclined lateral walls. These figures also show that the arytenoid structure bent and pushed the flow away from the posterior wall and helped the viscous boundary layer grow faster through the additional velocity component in the posterior to anterior direction.

For the sake of consistency, Fig. 5-15(a,b,c) are zoomed and fit in the same window as the cases without the arytenoid structure in Figures 5-16(a,b,c). These figures show the flow streamlines in the mid-sagittal plane focused on the glottis for the 10° convergent case (C16), 0° uniform case (U16), and 10° divergent case (D16), respectively, with the arytenoid cartilages structure. Similar to the corresponding cases without the arytenoid, in these cases, by changing the glottal angle from 10° divergent to 10° convergent, separation point positions occurred further downstream and the boundary layer thickness decreased.

The boundary layer thickness at the posterior end of the glottal exit was 32% of the anterior-posterior length for the divergent case and 15% for the convergent case. These boundary layer thicknesses can be seen in Fig. 5-17 to Fig. 5-19, especially for the 0° uniform case (U16) and 10° divergent case (D16) with the arytenoid structure, which the separation points occurred exactly at the glottal entrance and the boundary layer growth were observed at the exit line where the flow was reversed and the flow exiting the glottis contracted toward the mid-line. The large portion of the exit line in the divergent case with zero-length arrows shows the large thickness of the boundary layer and significant secondary flow.

Figures 5-17(a,b), Fig. 5-18(a,b), and Fig. 5-19(a,b) show the velocity profiles within the glottis in the mid-sagittal plane for the 10° convergent case (C16), 0° uniform case (U16), and 10° divergent case (D16), without and with the arytenoid
Figure 5-15: Flow streamlines in the mid-sagittal plane, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), with different glottal angles: a) convergent (C16), b) uniform glottis (U16), and c) divergent (D16). D=0.16 cm.
Figure 5-16: Flow streamlines in the mid-sagittal plane, focused on glottis, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), with different glottal angles: a) convergent (C16), b) uniform glottis (U16), and c) divergent (D16). D=0.16 cm.
structure, respectively. These figures show that, contrary to two-dimensional models like M5, flow contraction in the glottis existed in each case whether or not the arytenoid cartilages structure was present. This is one of the most important findings in this study. Also, they show that for the non-eccentric cases, the flow separations and boundary layers were symmetrical in the anterior and posterior ends. For the eccentric cases, because of the flow circulations and bending flow at the posterior end, the separation point at the end of the posterior glottis occurred more upstream than the anterior end, and the growth rate of the boundary layer at the posterior end was faster than at the anterior end. Therefore, not only were the flow patterns different for different glottal angles, they also were different in the anterior and posterior ends for each case. Comparing these three figures indicate that the boundary layer thickness at the posterior end of the glottis is higher than the anterior end by 50% to 60% (as seen in Chapter 4).
Figure 5-17: Sagittal velocity profiles within the glottis for convergent glottis (C16) for $\Delta p_T = 0.981$ kPa ($10$ cm H$_2$O), for two configurations: a) without the arytenoid structure, and b) with the arytenoid structure.
Figure 5-18: Sagittal velocity profiles within the glottis for uniform glottis with diameter of 0.16 cm (U16) for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for two configurations: a) without the arytenoid structure, and b) with the arytenoid structure.
Figure 5-19: Sagittal velocity profiles within the glottis for divergent glottis (D16) for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for two configurations: a) without the arytenoid structure, and b) with the arytenoid structure.
5.3 Variable Glottal Diameters

In this section, the cases with different glottal diameters are discussed. Similar to Section 3.3, the glottal diameters were 0.16 cm (U16), 0.04 cm (U04), and 0.01 cm (U01). For each case, the glottal shape was uniform (a glottal angle of 0°). The uniform case with glottal diameter of 0.16 cm (U16) was discussed in Section 5.2; it will be compared with other cases in this section. The glottal diameter effects were studied for two different conditions, with and without the arytenoid structure for a transglottal pressure of 0.981 kPa (10 cm H₂O).

5.3.1 Without arytenoid structure

5.3.1.1 Coronal plane

Figures 5-20(a,b) show the pressure contours within the glottis for the 0° uniform case with diameter of 0.04 cm (U04) in the anterior (1/4) (or equivalently posterior (3/4)) and the midcoronal planes, respectively, without the arytenoid cartilages structure. It should be noted that the scale of the y-axis was adjusted to see details better. Fig. 3-22 and Fig. 5-20 indicate that contrary to the case with a glottal diameter of 0.16 cm, there was only one pressure dip in this case and at the same axial distance (at the beginning of the glottal exit curvature). Furthermore, the pressure for the midcoronal plane was lower than for the anterior (1/4) plane up to glottal exit where the pressures were identical. Figures 5-20(a,b) also show that, similar to the 10° convergent case, for a short distance downstream of the entrance and before the separation points, the pressures became nearly constant perpendicular to the walls in both planes. The pressure values within the glottis decreased axially, and the adverse pressure gradient for flow separation was not created until the cross-sectional area increased near the end of the glottis duct. The separation points in both mid- and anterior (1/4) coronal planes occurred near the glottal exit at the same axial location.
of 2.07 mm (see Fig. 5-20(a,b)). Comparing the axial locations of the separation points for the two uniform cases of U16 and U04 shows that the locations of the separation points did not change significantly by changing the glottal diameter.

Figures 5-21(a,b) show the velocity profiles within the glottis for the 0° uniform case with diameter of 0.04 cm (U04) in the anterior (1/4) (or equivalently posterior (3/4)) and the midcoronal planes, respectively, without the arytenoid cartilages structure. Contrary to the uniform case with diameter of 0.16 cm which had sharp velocity gradients at the walls, the velocity profiles in this case had smoother gradients at the walls and the velocity profiles began to approach a parabolic shape within the glottis. Because the flow rate (118.6 cm$^3$/s) and glottal diameter (0.04 cm) were smaller than for the largest diameter case (447.8 cm$^3$/s, 0.16 cm), flow development was more developed prior to flow separation.

Figures 5-22(a,b) show the pressure contours within the glottis for the 0° uniform case with diameter of 0.01 cm (U01) in the anterior (1/4) (or equivalently posterior (3/4)) and the midcoronal planes, respectively, without the arytenoid cartilages structure. Again, the scale of the y-axis was adjusted to see details better. Flow visualizations showed that the flow skewed downstream of the glottis for this case. Since FLUENT only predicts a symmetric flow through a symmetric glottis and symmetric boundary conditions, the flow asymmetry could not be captured in the numerical results. To produce the skewed flow using FLUENT, a small linear pressure gradient (0-0.2 Pa across the duct downstream of the glottis) was imposed as a boundary condition. The same method of inducing an artificial non-symmetric flow has been applied in earlier studies [37, 38]. Both Fig. 3-22 and Fig. 5-22(a,b) indicate that, although similar to the case (U04), the intraglottal pressures decreased in the inferior to superior direction in both coronal planes and the pressure in the midcoronal plane was lower than in the anterior (1/4) plane, and in each plane the pressures on the walls were different near to the glottal exit. That is, contrary to the cases
Figure 5-20: Pressure contours at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.04 cm (U04): a) Anterior (1/4)-coronal, and b) Middle-coronal. Values of the contours are in kPa.
Figure 5-21: Coronal velocity profiles within the glottis at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.04 cm (U04): a) Anterior (1/4)-coronal, and b) Middle-coronal.
with larger glottal diameters, only in the uniform case with the smallest diameter of 0.01 cm (U01) did the flow skew and create different axial locations for the flow separation points on each wall. Using the same naming as in previous studies [37, 38, 40], the flow-wall (FW) had lower pressures than the non-flow-wall (NFW), and the flow skewed relative to the FW (lower wall in Fig. 5-22). The flow separations were at axial locations of 2.10 mm for the midcoronal plane on the FW and 2.02 mm on the NFW. For the anterior (1/4) plane flow separation started at the location of 2.06 mm on the FW and 2.04 mm on the NFW (see Fig. 5-22(a,b)). Similar to the case (U04), for a short distance downstream of the entrance and before the separation points, the pressures became essentially constant perpendicular to the walls in both planes. These figures also show that the pressure difference between the FW and NFW at the separation points was higher for the anterior (1/4) plane than for the midcoronal plane.

Figures 5-23(a,b) show the velocity profiles within the glottis for the 0° uniform case with diameter of 0.01 cm (U01) in the anterior (1/4) (or equivalently posterior (3/4)) and the midcoronal planes, respectively, without the arytenoid cartilages structure. In this case, the velocity gradients near the walls were much smoother than for the other two uniform cases which means that the flow was almost fully developed with the characteristic parabolic shape of the velocity profiles. Contrary to other cases with larger glottal diameters, the velocity profiles skewed just after the beginning of the glottal exit curvature. These figures and Fig. 5-22 also show that due to higher pressure difference between the FW and NFW at the separation points for the anterior (1/4) plane than for the midcoronal plane, the skewness angle was greater for the anterior (1/4) plane (about 45°) than for the midcoronal plane (about 40°). This finding is compatible with the results obtained in Chapter 4. Comparing all the uniform cases with different glottal diameters shows that by decreasing the glottal diameter, intraglottal pressures decreased axially with a greater slope and the
Figure 5-22: Pressure contours at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.01 cm (U01): a) Anterior (1/4)-coronal, and b) Middle-coronal. Values of the contours are in kPa. Small pressure gradient (0-0.2 Pa) was imposed as a boundary condition across the duct downstream of the glottis.
Figure 5-23: Coronal velocity profiles within the glottis at different coronal planes, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.01 cm (U01): a) Anterior (1/4)-coronal, and b) Middle-coronal. Small pressure gradient (0-0.2 Pa) was imposed as a boundary condition across the duct downstream of the glottis.
velocities became more fully developed before the separation points, increasing the chance for flow skewness.

5.3.1.2 Sagittal plane

Figures 5-24(a,b,c) show the flow streamlines in the mid-sagittal plane for the 0° uniform cases with diameters of 0.01 cm (U01), 0.04 cm (U04), and 0.16 cm (U16), respectively, without the arytenoid cartilages structure. The results of Section 5.2 indicated that because of the curved shaping of the glottis, there was creation of flow from the anterior and posterior sections toward the center of the glottal duct, as well as a contracting jet downstream of the glottis. These observations were also seen in the uniform cases for all glottal diameters, and especially for the smallest diameter case (see Fig. 5-24a). The streamlines of these figures show that separation occurred at the anterior and posterior ends, upstream of the glottal exit, for all three cases, and that the secondary cross flow effect relative to extension toward the center of the glottis was greater with the smallest diameter (also see Fig. 5-32). Thus, the faster-growing viscous boundary layer at the anterior and posterior ends with decreasing glottal diameter created greater three-dimensionality effects of the flow.

The boundary layer thickness at the glottal exit changed from 56% of the anterior-posterior length for case U01 to 18% for case U16. These boundary layer thicknesses can be seen in Fig. 5-18, Fig. 5-31, and Fig. 5-32, especially at the exit line where the flow was reversed and the flow exiting the glottis constricted toward the mid-line. The large portion of the exit line in the uniform case with diameter of 0.01 cm (U01) with zero-length arrows shows the large thickness of the boundary layer and significant secondary flow (see also Chapter 4).
Figure 5-24: Flow streamlines in the mid-sagittal plane, without the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm $H_2O$), with different glottal diameters: a) diameter of 0.01 cm (U01), b) diameter of 0.04 cm (U04), and c) diameter of 0.16 cm (U16).
5.3.2 With arytenoid structure

5.3.2.1 Coronal plane

Figures 5-25(a,b,c) show the pressure contours within the glottis for the $0^\circ$ uniform case with diameter of 0.04 cm (U04) in the anterior (1/4), midcoronal, and posterior (3/4) planes, respectively, with the arytenoid cartilages structure present. Fig. 3-29 and Fig. 5-25 indicate that the intraglottal pressures were different at the glottal entrance, but similar to the cases without the arytenoid cartilages structure. The pressure for the midcoronal plane was lower than for the anterior (1/4) plane up to the glottal exit, where the pressures were identical. Figures 5-25(a,b,c) also show that, similar to the $0^\circ$ uniform case (U04) without the arytenoid structure, for a short distance downstream of the entrance and before the separation points, the pressures became essentially constant perpendicular to the walls in both planes. In general, the flow behaviors for the cases with and without the arytenoid structure were almost the same and the arytenoid structure did not change the flow specifications drastically except in a small area near the posterior end. Therefore, the separation points in both mid- and anterior (1/4) coronal planes occurred near the glottal exit at the same axial location of 2.07 mm, similar to that discussed in Section 5.3.1.1 (see Fig. 5-25).

Figures 5-26(a,b,c) show the velocity profiles within the glottis for the $0^\circ$ uniform case with diameter of 0.04 cm (U04) in the anterior (1/4), midcoronal, and posterior (3/4) planes, respectively, with the arytenoid cartilages structure present. Similar to the uniform case without the arytenoid structure, the velocity profiles had smooth gradients near the walls and velocity profiles began to alter toward the parabolic shape within the glottis, but the separation occurred before reaching a fully developed flow.

Fig. 3-29 and Fig. 5-27(a,b,c) show that, for the 0.01 cm (U01) case, similar to the corresponding case without the arytenoid structure, the intraglottal pressures decreased in the inferior to superior direction for the three coronal planes and the
Figure 5-25: Pressure contours at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.04 cm (U04): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. Values of the contours are in kPa.
Figure 5-26: Coronal velocity profiles within the glottis at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.04 cm (U04): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal.
pressures in the anterior (1/4) and posterior (3/4) planes were higher than the mid-coronal plane up to the glottal exit. Similar to the corresponding case without the arytenoid structure, flow visualizations showed the flow skewness in this case, and therefore a linear pressure gradient was imposed across the duct downstream of the glottis as a boundary condition. The pressures on the walls were different near the glottal exit. In addition, the flow skewed and caused different axial locations of the flow separation points on each wall. Again, the flow separations were at an axial location of 2.10 mm for the midcoronal plane on the FW and 2.02 mm on the NFW, and for the anterior (1/4) plane flow separation was at the location of 2.06 mm on the FW and 2.04 mm on the NFW (see Fig. 5-27(a,b,c)). It should be noted that the absence or presence of the arytenoid structure did not change the flow behavior intensively (i.e., the existence of relatively constant pressures perpendicular to the walls in both planes) or the locations of the separation points for each plane.

Figures 5-28(a,b,c) show the velocity profiles within the glottis for the 0° uniform case with diameter of 0.01 cm (U01) in the anterior (1/4), midcoronal, and posterior (3/4) planes, respectively, with the arytenoid cartilages structure present. Similar to the corresponding case without the arytenoid structure, the flow is almost fully developed with the characteristic parabolic shape of the velocity profiles, unlike the other two diameter cases. Also in this case, the velocity profiles skewed just after the beginning of the glottal exit curvature. Therefore, the locations of the flow separation points as well as the skewness angle did not change in the presence of the arytenoid structure (see Fig. 5-28).

5.3.2.2 Sagittal plane

Figures 5-29(a,b,c) show the flow streamlines in the mid-sagittal plane for the 0° uniform cases with diameters of 0.01 cm (U01), 0.04 cm (U04), and 0.16 cm (U16), respectively, with the arytenoid cartilages structure present. As these figures show,
Figure 5-27: Pressure contours at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa ($10$ cm H$_2$O), for uniform glottis with diameter of $0.01$ cm (U01): a) Anterior ($1/4$)-coronal, b) Middle-coronal, and c) Posterior ($3/4$)-coronal. Values of the contours are in kPa. Small pressure gradient (0-0.2 Pa) was imposed as a boundary condition across the duct downstream of the glottis.
Figure 5-28: Coronal velocity profiles within the glottis at different coronal planes, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for uniform glottis with diameter of 0.01 cm (U01): a) Anterior (1/4)-coronal, b) Middle-coronal, and c) Posterior (3/4)-coronal. Small pressure gradient (0-0.2 Pa) was imposed as a boundary condition across the duct downstream of the glottis.
the flow patterns were not symmetric in the posterior-anterior direction for all three cases, but more obvious for the case with the glottal diameter of 0.16 cm (U16). Figure 5-29a show that for the 0° uniform case with diameter of 0.01 cm (U01), since both the glottal diameter and flow rate were small, the glottis resistance was high, and therefore flow circulations were occurred in both upstream and downstream of the glottis. As seen in Section 5.3.2.1, the arytenoid structure had more three-dimensional effects on the flow patterns for the maximum glottal diameter for the uniform cases and other two lower diameters of the glottis remained nearly unchanged. For the maximum glottal diameter case (U16), the arytenoid structure bent and pushed the flow away from the posterior wall and helped the viscous boundary layer grow faster through the additional velocity component in the posterior to anterior direction. Similar to the case without the arytenoid structure, the streamlines of these figures show that the separations occurred at the anterior and posterior ends, upstream of the glottal exit (also see Fig. 5-18, Fig. 5-31, and Fig. 5-32).

For the sake of consistency, Fig. 5-29(a,b,c) are zoomed and fit in the same window of the cases without the arytenoid in Figures 5-30(a,b,c). These figures show the flow streamlines in the mid-sagittal plane focused on the glottis for the 0° uniform cases with diameters of 0.01 cm (U01), 0.04 cm (U04), and 0.16 cm (U16), respectively, with the arytenoid cartilages structure present. Contrary to the case without the arytenoid structure, Fig. 5-30a show that due to presence of the arytenoid structure, low flow rate, and high glottal resistance, the flow circulations occurred in the upstream of the glottis which changed the flow streamlines in the posterior end, but the flow passing the glottis was almost the same for the cases with and without the arytenoid structure. These figures show that although the arytenoid structure for the uniform case with the glottal diameter of 0.16 cm (U16) made maximum bending of the streamlines and caused the boundary layer thickness grow faster in the posterior end (25% of the anterior-posterior length), still the boundary layer thickness at the posterior end for
Figure 5-29: Flow streamlines in the mid-sagittal plane, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), with different glottal diameters: a) diameter of 0.01 cm (U01), b) diameter of 0.04 cm (U04), and c) diameter of 0.16 cm (U16).
Figure 5-30: Flow streamlines in the mid-sagittal plane, focused on glottis, with the arytenoid structure, for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), with different glottal diameters: a) diameter of 0.01 cm (U01), b) diameter of 0.04 cm (U04), and c) diameter of 0.16 cm (U16).
the uniform case with glottal diameter of 0.01 cm (U01) had the greatest thicknesses (33% of the anterior-posterior length). A comparison of all the uniform cases with the different glottal diameters, with and without the arytenoid structure, indicates that the flow behavior changed mainly for the case with the highest glottal diameter (U16) in the presence of arytenoid structure.

Figure 5-31: Sagittal velocity profiles within the glottis for uniform glottis with diameter of 0.04 cm (U04) for $\Delta p_T = 0.981$ kPa (10 cm H$_2$O), for two configurations: a) without the arytenoid structure, and b) with the arytenoid structure.
Figure 5-32: Sagittal velocity profiles within the glottis for uniform glottis with diameter of 0.01 cm (U01) for $\Delta p_T = 0.981$ kPa ($10 \text{ cm H}_2\text{O}$), for two configurations: a) without the arytenoid structure, and b) with the arytenoid structure.
Chapter 6

Discussion

6.1 Introduction

Model M6 is an empirical static model through which air flows at a constant rate to obtain detailed pressure distributions on the vocal fold surfaces. These distributions act as driving pressures during phonation when applied to multimass analytic computer models, and can be used to test the pressure and flow accuracies of computational models. Most of the previous studies in the phonation field dealt with simplified (rectangular) models of the vocal folds. In those models, the glottis is considered to have a two-dimensional geometry and the flow specifications were studied in the midcoronal plane. Model M6 has more realistic (half-sinusoidal) vocal fold surfaces and it allows the investigation of the pressure differences along the anterior-posterior direction with three pressure tap lines at the middle, anterior (1/4), and posterior (3/4) locations. In addition, model M6 can include a single modeled arytenoid cartilages structure based on a simplified rendition of pictures and dimensions of the arytenoid cartilages. The presence of the arytenoid structure creates an eccentricity of the glottis within the airway between the trachea and hypopharynx. Due to a more realistic glottal geometry, the results of this study maybe more accurate for
phonation and more realistically applicable to simulation models. The pressure and flow values can be considered benchmark data.

Thus, this research project studied a novel, more realistic model of the larynx that includes not only a more realistic curvature of the glottis but also the eccentricity of the glottis due to the presence of the arytenoid structure. It was anticipated that these structures would alter the pressure distributions in the axial direction, the pressure gradients in the anterior-posterior (A-P) direction, and the corresponding flows and velocities within and downstream of the glottis.

6.2 Pressures and Velocities

6.2.1 Reynolds number and laminarity

The Reynolds number is calculated as Re = UD_H/ν, based on the hydraulic diameter of the glottis, \( D_H = 4A/P \), and the kinematic viscosity of air, \( \nu = 1.5 \times 10^{-5} \) m\(^2\)/s. Given the sinusoidal geometry of the vocal fold medial surface in the model, the minimum transverse area is \( A = 2D_GL/\pi \) and its perimeter is \( P = 2 \int_0^L [1 + (\pi D_G/2L)^2 cos^2(\pi y/L)]^{1/2} dy \), such that \( D_H \) is 0.2 cm. The Reynolds numbers are in the range \( 2800 < Re < 8500 \) for this study, which are common for phonation. Despite these values of Re, flow visualizations in this work (see Chapter 4) and prior studies (e.g., Shinwari et al. [40], Kucinschi et al. [23], Neubauer et al. [29]) suggest laminar flow inside the glottis for both static and oscillating larynx models. However, the flow is observed to become turbulent further downstream of the glottis. The laminar glottal flow regime explains the quasi-identical dimensionless intraglottal pressure distributions shown in Fig. 3-4 to Fig. 3-9 for any given geometry and coronal section. This suggests that the flow regime in the glottis does not change to turbulence with changes in the transglottal pressure.
6.2.2 Computational model justification

While the pressures can be measured experimentally on the glottal walls, it is more difficult to measure velocities inside the M6 glottis because of the limited optical access. This difficulty is common for all physical models, where the PIV technique is typically used only downstream of the glottis [44, 45]. The velocity fields, together with the complete pressure fields, can be obtained by means of CFD simulations. Since the experimental wall pressures and flow rates are well matched computationally, one can infer that the velocities are also correctly predicted throughout the glottis.

6.2.3 Variable glottal angles: midsagittal velocities

The numerically calculated midsagittal velocities at the middle, anterior (1/4), and posterior (3/4) coronal sections for the three glottal shapes at the minimal glottal locations (when the arytenoid structure is not present) are presented in Table 6.1. The first observation is that the velocities (in m/s, real life values) are slightly greater away from mid-line. The anterior (1/4) (or posterior (3/4)) locations have axial velocities 1.15 - 3.54 % higher than at the mid-line. This finding is consistent with the PIV velocity measures of Khosla et al. [19], who measured velocities 0.3 cm from the glottal exit. They found that velocities in the midsagittal plane of the glottis were typically slightly greater away from the anterior-posterior center plane (refer to their Fig. 3). The greater velocity found in the anterior portion of the glottis compared to other locations more posterior by Berke et al. [7], Alipour and Scherer [3], and Bielamowicz et al. [8] (who found large increases anteriorly) may be due more to subtle dynamic glottal configurations during phonation. Thus, without the arytenoid, the glottal curvature effect alone was to alter the A-P velocities with higher velocities at the midcoronal location, but these velocities differ by less than 4%. Thus, computer
Table 6.1: Computational axial velocities in m/s (real life) at the middle, anterior (1/4), and posterior (3/4) sections for the three glottal shapes without the arytenoid structure at the minimal glottal locations, for two values of the transglottal pressure, $\Delta p_{T,1}=0.294$ kPa, and $\Delta p_{T,2}=2.453$ kPa. The M6 computational results correspond to the finest grid in Table 2.2.

<table>
<thead>
<tr>
<th></th>
<th>Case (C16)</th>
<th>Case (U16)</th>
<th>Case (D16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta p_{T,1}$</td>
<td>21.57</td>
<td>20.20</td>
<td>22.86</td>
</tr>
<tr>
<td>$\Delta p_{T,2}$</td>
<td>61.57</td>
<td>57.37</td>
<td>66.53</td>
</tr>
<tr>
<td>Ant.,Post.</td>
<td>21.33</td>
<td>19.66</td>
<td>22.32</td>
</tr>
<tr>
<td>Middle</td>
<td>60.82</td>
<td>57.34</td>
<td>64.67</td>
</tr>
</tbody>
</table>

modeling would be rather accurate to use essentially constant velocities in the A-P direction at the minimal cross section, unless greater accuracy were needed.

The effect of eccentricity was to alter these velocities at the minimal cross sections for the different glottal angles. Table 6.2 indicates that the velocities at the minimal cross section now show differences between the anterior (1/4) and posterior (3/4) locations when the arytenoid structure is present. The relation depends on glottal angle, however. For the convergent case, the velocities are slightly higher posteriorly, for the uniform slightly lower posteriorly, and for the divergent case slightly lower, also. However, these velocities differ by less than 3% of each other, and furthermore the middle velocity (less for convergent and uniform, more for divergent) differs from the others by no more than 4%. In general, then, curvature and eccentricity had little effect on creating different axial velocities at the three coronal locations at the minimal glottal cross sections. This is consistent with measures of laminar core lengths at the same locations in the flow exiting the glottis, where negligible differences were found due to curvature and eccentricity.
Table 6.2: Computational axial velocities in m/s (real life) at the middle, anterior (1/4), and posterior (3/4) sections for the three glottal shapes with the arytenoid structure at the minimal glottal locations, for two values of the transglottal pressure, \( \Delta p_{T,1} = 0.294 \) kPa, and \( \Delta p_{T,2} = 2.453 \) kPa. The M6 computational results correspond to the finest grid in Table 2.2.

<table>
<thead>
<tr>
<th>Case</th>
<th>( \Delta p_{T,1} )</th>
<th>( \Delta p_{T,2} )</th>
<th>( \Delta p_{T,1} )</th>
<th>( \Delta p_{T,2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>21.89</td>
<td>62.60</td>
<td>20.47</td>
<td>58.14</td>
</tr>
<tr>
<td>Middle</td>
<td>21.55</td>
<td>61.66</td>
<td>19.66</td>
<td>57.82</td>
</tr>
<tr>
<td>Posterior</td>
<td>21.96</td>
<td>62.85</td>
<td>19.85</td>
<td>58.01</td>
</tr>
</tbody>
</table>

6.2.4 Variable glottal diameters: midsagittal velocities

The suggested finding that the velocities at the minimal cross section are about the same despite curvature and eccentricity for the different glottal angles (for a diameter of 0.16 cm) was not supported completely for the uniform glottis diameter variations. For the diameter series with the uniform glottis, and without eccentricity, the velocities near the glottal exit (at the tap #11 location) were nearly identical (below 3%) among the three distribution locations for the two larger diameters, but as much as 13.1% different for the smallest diameter case for transglottal pressure of 0.294 kPa (3 cm \( H_2O \)) between the midcoronal and the other two positions. It would have been quite convenient for the velocity to be uniform along the anterior-posterior direction of the glottis for multimass models. This would allow for easy calculation of volume flow within each glottal “channel” for such models. The results here suggest that this approach may be adequate for larger diameters; but for smaller diameters, for better accuracy in estimating the total glottal flow, one would have to take into consideration the empirical differences in velocity for each channel relative to both glottal diameter and transglottal pressure.

The computed midsagittal velocities at the middle, anterior (1/4), and posterior
Table 6.3: Computational axial velocities in m/s (real life) at the middle, anterior (1/4), and posterior (3/4) sections for the three glottal diameters without the arytenoid structure at the glottal exit (tap #11), for two values of the transglottal pressure, $\Delta p_{T,1}=0.294$ kPa (3 cm H$_2$O), and $\Delta p_{T,2}=2.453$ kPa (25 cm H$_2$O). The M6 computational results correspond to the finest grid in Table 2.2.

<table>
<thead>
<tr>
<th></th>
<th>Case (U01)</th>
<th>Case U(04)</th>
<th>Case U(16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta p_{T,1}$</td>
<td>$\Delta p_{T,2}$</td>
<td>$\Delta p_{T,1}$</td>
<td>$\Delta p_{T,2}$</td>
</tr>
<tr>
<td>Ant.,Post.</td>
<td>12.16</td>
<td>47.24</td>
<td>18.17</td>
</tr>
<tr>
<td>Middle</td>
<td>13.99</td>
<td>49.61</td>
<td>18.68</td>
</tr>
</tbody>
</table>

(3/4) coronal sections for three glottal diameters near the glottal exit (tap #11) locations are presented in Table 6.3. The velocities are slightly smaller away from the mid-line in case (U01) and case (U04), with differences of 13.1% and 4.8% for case (U01), 2.7% and 2.2% for case (U04), and -2.7% and 0.0% for the lower and higher transglottal pressures, respectively. The specific reason for these differences is not clear, but may be related to the degree of fully developed flow at each coronal section.

The effect of eccentricity on the velocities at the three coronal locations for the various diameters are given in Table 6.4, where there is still a significant difference between the three locations for the smallest diameter U01 (10.9% for 0.294 kPa and 6.3% for 2.453 kPa, but less than about 4% for the other diameters. The anterior and posterior velocities differed by less than 3% across all three diameters for both transglottal pressures.

Thus, in general there are only small differences among the velocities along the A-P direction of the glottis due to either curvature or eccentricity, except at small diameters where the velocities are expected to be greater in the middle coronal plane by approximately 10-13% compared to 1/4 and 3/4 of the distance along the glottis.
Table 6.4: Computational axial velocities in m/s (real life) at the middle, anterior (1/4), and posterior (3/4) sections for the three glottal diameters with the arytenoid structure at the glottal exit (tap #11), for two values of the transglottal pressure, $\Delta p_{T,1}=0.294$ kPa (3 cm H$_2$O), and $\Delta p_{T,2}=2.453$ kPa (25 cm H$_2$O). The M6 computational results correspond to the finest grid in Table 2.2.

<table>
<thead>
<tr>
<th></th>
<th>Case (U01)</th>
<th>Case U(04)</th>
<th>Case U(16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>13.20</td>
<td>50.57</td>
<td>19.08</td>
</tr>
<tr>
<td>Middle</td>
<td>14.71</td>
<td>53.66</td>
<td>19.22</td>
</tr>
<tr>
<td>Posterior</td>
<td>13.11</td>
<td>50.24</td>
<td>19.01</td>
</tr>
</tbody>
</table>

6.2.5 Intraglottal pressure distributions: 2D vs. 3D models

The glottis is rectangular in the transverse plane in many prior models (henceforth referred to as 2D models), such that the coronal section is identical at any location along the anterior-posterior direction. Due to the large ratio of anterior-posterior distance to glottal diameter, the glottal flow can be considered to be essentially two-dimensional [37, 40]. This section compares the M6 results to the rectangular configuration in order to show the significance of the three-dimensional effects on the wall pressures. Here the two-dimensional version of FLUENT was used to solve the 2D (rectangular) cases whose geometry corresponds to both the 0.16 cm diameter of the midcoronal section of M6, and the 0.113 cm diameter of the anterior (1/4) or posterior (3/4) coronal sections of M6. The following discusses the results for two glottal shapes (i.e., 1.2 cm×0.16 cm and 1.2 cm×0.113 cm, rectangular form), compared to the M6 half-sinusoidal arcs, non-rectangular shape, at identical coronal cross-sections. The method of using two-dimensional CFD simulations for rectangular models was validated in prior studies [1, 37, 38, 23].

Figure 6-1 presents the intraglottal pressures for half-sinusoidal (i.e., M6) and for the rectangular glottis for the six configurations, i.e., 10° convergent, 0° uniform, and
10° divergent, in the middle (0.16 cm) and anterior (1/4) / posterior (3/4) coronal (0.113 cm) cross-sections. The 2D pressure drops for the 0.16 cm glottis are consistently larger than those obtained for M6 in the middle coronal cross section. The largest differences for all cases occur just upstream of the glottal entrance, near the end of the convergent inlet zone. For the convergent and uniform geometries, the 2D pressure distributions for the anterior (1/4) section (0.113 cm) are relatively close to both the M6 anterior (1/4) and M6 midsection distributions throughout the glottis. The convergent glottis velocity profiles in the glottal entrance and near the glottal exit are consistent with these results, as shown in Fig. 6-2. The entrance velocities for the two-dimensional 0.16 cm section are larger than for the three-dimensional (M6) middle section, which is consistent with the larger pressure drop.

Table 6.5 presents the flow rates in the 2D section cases and the corresponding M6 sections. For the 10° convergent, 2D larynx with the midsection diameter (0.16 cm), the flow rates are approximately 54% larger than for M6 for all the transglottal pressures, while for the 2D larynx with the anterior (1/4) section diameter (0.113 cm) the flow rates are only approximately 9.5% larger than for M6. For the uniform geometry, the flow rates in the 2D cases with mid- and anterior (1/4) section diameters are approximately 60% and 12% larger, respectively, than for M6. The largest differences occur for the 10° divergent case, where the flow rates for the 2D midsection are between 62% and 73% larger than for M6, while for the 2D anterior (1/4) section they are between 17.5% and 26% larger than for M6. The pressure and flow rate data suggest that the overall glottal flow resistance for the M6 sinusoidal geometry is greater than for a rectangular geometry with the same nominal diameter. This behavior is related to the minimum transverse area (usually known as the “projected glottal area”), which for M6 is 0.122 cm$^2$ for all three glottal angles. For the rectangular cases with 0.16 cm and 0.113 cm diameters, the minimum transverse areas are 0.192 cm$^2$ and 0.136 cm$^2$, respectively, for the anterior-posterior length of 1.2 cm.
Figure 6-1: Comparison between the pressure distributions in M6 (mid-coronal and anterior (1/4) coronal plane) with the pressure distributions in similar two-dimensional geometries, for a transglottal pressure of 0.981 kPa (10 cm H$_2$O). The M6 mid-coronal results are represented with a continuous line, and M6 anterior (1/4) plane with a dashed line. The two-dimensional pressures are represented with dash-dot line (−·) for the mid-coronal, and dash-dot-dot (−··) line for the anterior (1/4) plane. The uniform distributions (“U16”) are identified by the symbol (○), and the divergent ones (“D16”) by (△). No symbol is used for the convergent distributions (“C16”).
Figure 6-2: Axial velocity profiles in midcoronal and anterior (1/4) planes at glottal entrance (tap #6 position, x=0) and near exit (tap #11 position) (symbol ◦) for the convergent case. Comparison between M6 and the corresponding two-dimensional cases, for a transglottal pressure of 0.981 kPa (10 cm H₂O). The M6 mid-plane results are represented by a continuous line, and the M6 anterior (1/4) plane by a dashed line (---). The two-dimensional pressures are represented with dash-dot line (−−) for the mid-plane, and dash-dot-dot (−··) line for the anterior (1/4) plane. The lines with symbols are for the near-exit velocity profiles.
Table 6.5: Comparison between the calculated M6 flow rates (in cm³/s, real life), and flow rates calculated in the two-dimensional geometries corresponding to the anterior and middle planes in M6, for different values of transglottal pressure, $\Delta p_T$. The M6 computational results correspond to the finest grid in Table 2.2.

<table>
<thead>
<tr>
<th>$\Delta p_T$ [kPa]</th>
<th>Case (C16) M6 2D (Ant) (Mid)</th>
<th>Case (U16) M6 2D (Ant) (Mid)</th>
<th>Case (D16) M6 2D (Ant) (Mid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.294</td>
<td>269.9 296.6 418.1</td>
<td>256.3 289.2 411.4</td>
<td>287.3 337.7 465.4</td>
</tr>
<tr>
<td>0.491</td>
<td>351.0 384.8 542.3</td>
<td>335.7 377.7 535.7</td>
<td>374.2 440.9 606.5</td>
</tr>
<tr>
<td>0.981</td>
<td>500.2 546.8 770.2</td>
<td>482.8 541.4 765.0</td>
<td>533.3 631.7 867.2</td>
</tr>
<tr>
<td>1.472</td>
<td>614.7 671.2 945.0</td>
<td>596.2 667.6 941.4</td>
<td>640.3 778.7 1068.1</td>
</tr>
<tr>
<td>1.962</td>
<td>711.2 776.4 1092.2</td>
<td>690.4 774.3 1090.4</td>
<td>738.2 902.9 1237.8</td>
</tr>
<tr>
<td>2.453</td>
<td>796.3 869.3 1221.8</td>
<td>774.2 868.4 1221.7</td>
<td>800.9 1012.5 1387.6</td>
</tr>
</tbody>
</table>

One can observe that flow rate, $Q$, and area, $A$, are proportional for the same pressure drop. The area ratio between the 2D midsection (0.16 cm²) and M6 was 0.192 cm²/0.122 cm² or 57% higher, and for the 2D anterior (1/4) section (0.113 cm²) and M6 midsection 0.138 cm²/0.122 cm² or 11% higher. These percentages match the flow rate ratios well for the convergent and uniform glottis. This proportionality suggests that if the same mean velocity, $U = Q/A$, is maintained, then the Bernoulli equation, $U = K_t \sqrt{2\Delta p/\rho}$, may be applied for the same pressure drop ($\Delta p$). That is, for a given transglottal pressure, at the minimum glottal diameter, one of the three (volume flow, area, velocity) can be predicted given the other two.

Figure 6-1 shows that for the convergent geometry the maximum values of pressure drop occur just upstream of the glottal exit (at about 2 mm), and are similar for all sections (either 2D or M6), which explains the apparent success of Bernoulli for this case. For the uniform geometry, Fig. 6-1 shows that the maximum pressure drop occurs slightly upstream of glottal entrance (x=0 mm), and shows modest variations between different 2D or M6 sections, such that again Bernoulli appears to work. It could be thus inferred that Bernoulli could be used to estimate the flow rates for
the convergent and uniform glottal shapes. However, much larger variations of \( \Delta p \) are observed for the divergent glottal shape, such that the \textit{ad hoc} application of the Bernoulli equation would lead to severe overpredictions of the flow rate. This shows that the Bernoulli equation fails to produce accurate estimations of flows through a three-dimensional glottis. More accurate analytic models exist [32, 10], but they are less intuitive than the Bernoulli equation, and applicable only to two-dimensional (rectangular) geometries.

One can also conclude that it is generally incorrect to assume a rectangular model can provide reliable data for a three-dimensional glottis having the same area. It is questionable that the inaccuracies are less for smaller minimum mid-coronal diameters, given the greater differences in velocities found for the 0.01 cm diameter uniform case (see Table 6.3).

6.2.6 M6 pressure gradients within the glottis

This section examines the curvature and eccentricity effects on the intraglottal pressure gradients in the A-P direction. A primary goal of this study was to determine how curvature and eccentricity alter pressures within the glottis. A 2D glottis essentially has constant pressures in the A-P direction, whereas those pressures are expected to alter with curvature and eccentricity of the glottis.

Figure 6-3 is a summary of the relative pressures at the three locations, anterior (1/4), midcoronal, and posterior (3/4) locations of the glottis where empirical pressures were measured. The first column relates to the various cases of the study (of which there are 10), including both the glottal angle series and the glottal diameter series (U16 is in both but appears only once). The next three columns indicate the relative pressures at the entrance to the glottis (tap #6), and the fifth column a simple diagram of the relative pressures of columns 2-4. Columns 6-8 indicate the relative pressures well within the glottis, that is, from taps #7 through #9 approximately,
prior to the glottal exit where there was always exit curvature. The last column on the right is again a simple diagram of the pressure gradient indicated in columns 6-8.

The plus, zero, and minus signs within the cells are explained as follows. If the anterior (1/4) pressure is greater than the midcoronal pressure, the anterior (1/4) pressure is given as a plus (+), and is circled if it is greater in value by at least 4% of the transglottal pressure. If it is less than the midcoronal pressure, it is given as a minus sign (-), and is circled if the difference is at least 4% of the transglottal pressure. The 4% criterion was arbitrary but seemed like a reasonable choice, even though the real criterion should be based on a difference that makes a real difference in vocal fold motion or glottal flows and velocities. The table rows indicate the 10 cases, with and without the presence of the arytenoid structure, that is, with and without eccentricity.

Figure 6-3 answers two questions of this study, (1) what types of A-P gradients are created by the glottal curvature, and (2) what alterations of those gradients occur due to the inclusion of eccentricity?

First it is observed that, overall, the dominant A-P pressure gradient in the glottis is a “down-up” gradient in which the midcoronal pressure is lower than at the anterior (1/4) or posterior (3/4) locations, since the “down-up” gradient occurs 11 out of the 20 conditions. The dominating condition for the down-up gradient was for smaller diameters with uniform glottal angles for either non-eccentric or eccentric conditions (U01, U04), where 7 of the 8 conditions were down-up gradients. This suggests that narrow glottal configurations with curvature may have a dominant bi-directional pressure gradient (as described in Alipour and Scherer [4]), with less pressure pushing against the midcoronal location, and more pressure anterior and posterior to that midmembranous location.

When the glottis was wide, as in the angle series, where the diameter was 0.16 cm, there was also the suggestion that the down-up gradient pattern dominated, given
<table>
<thead>
<tr>
<th>Case</th>
<th>At the Glottal Entrance</th>
<th>Within the Glottis</th>
<th>Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tap #6 Ant</td>
<td>Tap #6 Mid</td>
<td>Tap #6 Pos</td>
</tr>
<tr>
<td>C16_NA</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>C16_WA</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>U16_NA</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>U16_WA</td>
<td>-</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>D16_NA</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>D16_WA</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>U01_NA</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>U01_WA</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>U04_NA</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>U04_WA</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
</tbody>
</table>

Figure 6-3: Pressure Gradients in the Anterior-Posterior Direction in the Glottis. “+” means pressure is higher than at mid, “−” lower than at mid, and 0 same as at mid. A circle around the symbol indicates a difference of at least 4% of $\Delta p_T$ from the middle. A dashed circle means the Anterior-Posterior gradient is more than 7% of $\Delta p_T$. 

189
that three of the 6 gradients without eccentricity were of the down-up type. The other three were constant (straight across pattern) and up-down.

Figure 6-3 also provides arrows to indicate how the gradient pattern changed when eccentricity was introduced by the use of the arytenoid structure. Interestingly, the introduction of eccentricity altered the patterns most of the time. Of the 10 transitions, only 4 patterns (all down-up) were retained. Otherwise, the patterns changed, and curiously in 6 different ways (see Fig. 6-3). Perhaps also surprising is that a gradient with monotonic change (only decreasing or only increasing) occurred only 3 out of possible 20 patterns.

Some plus and minus symbols are circled. These values are considered here “significantly” different from the midcoronal values. This indicates the “strength” of the gradient pattern when both the anterior (1/4) and posterior (3/4) symbols are circled, as they are in 7 of 8 cases for the U01 and U04 conditions, all with the down-up gradient pattern. Thus the pattern is not only consistent but strong. Also, eccentricity did not alter the pattern.

For the large diameter cases, however, the gradient patterns are weak, in that only two (C16_−NA for tap #6, D16_−NA for tap #6) have two circles. The U16_−WA for tap #6 is also considered strong in that the entire gradient (monotonic) has a difference of about 7% of the transglottal pressure.

The eccentricity can strengthen or weaken the gradient pattern. For example, C16_−NA has a strong down-up pattern (two circles), but when the eccentricity is added, the pattern is the same but is weakened (no circles). On the other hand, U16_−NA has three zeros, indicating there is no real gradient and all three A-P values are about the same. However, when the eccentricity is introduced, a relatively strong monotonically increasing pressure gradient is created.

For the large diameter cases, there is an interesting eccentricity trend of some significance. When eccentricity is introduced, there is a tendency for the anterior
pressure to reduce relative to the midcoronal pressure. This occurs 5 out of the 6 cases (combining tap #6 and taps #7-9 cells). There is no such trend for the posterior (3/4) cases for the large diameter cases.

Of considerable interest is the difference in gradient patterns at tap #6 at glottal entry compared to taps #7-9 in the glottis. Of the 10 conditions (with and without eccentricity, that is, the 10 rows in Fig. 6-3), only 4 of the 10 shared the same A-P pressure gradient patterns, with 3 of those 4 being for the smaller diameters U01 and U04, the fourth from D16..NA. This is quite curious. A smaller diameter may “couple” the entrance and mid-glottal aerodynamics more strongly than larger diameters.

Thus, the primary findings relative to A-P pressure gradients are the following:

(1) Of the 7 types of pressure gradient patterns found, the dominant pattern was larger-to-smaller-to-larger pressures, that is, the “down-up” or “bi-directional” pressure gradient, where the midcoronal pressures were smallest. This pattern also had the greatest “strength”. This suggests that differential effects of the driving pressures in the A-P direction may be present especially for smaller glottal widths in the first half of the glottal opening phase and the second half of the glottal closing phase during a vibratory cycle.

(2) The pressure gradient patterns for the large diameter cases tend to be weak, where the pressures in the A-P direction do not differ more than the 4% of the trans-glottal pressure, with or without the eccentricity, suggesting that large differential effects of pressures in the A-P direction are not expected during the phonatory cycle when the glottis is relatively wide open.

(3) Eccentricity altered the pressure gradient pattern in most of the cases compared to the non-eccentric cases. Results suggest that the eccentricity could strengthen or weaken the pressure gradients with the patterns. Introduction of the eccentricity tended to decrease the relative pressure at the anterior (1/4) location relative to the midcoronal pressure for the larger diameter cases. These effects are most likely due
to the change in secondary (cross) flow intensities caused by the eccentricity.

(4) The pressure gradient pattern at glottal entrance tap #6 was similar to the pattern in the glottis beyond the entrance (taps #7-9) only for the smaller diameters and the divergent 0.16 cm diameter case. Otherwise, the pattern at glottal entrance was different from that inside the glottis, creating a curious situation. This suggests that a narrower glottis or glottal divergence “couples” the A-P pressure gradient patterns across the entire glottal axial duct length more strongly than do larger diameters.

### 6.3 Flow Contraction

The flow contractions, and secondary flow found in this study will be discussed in two sections. In the first section, the flow data resulting from the M6 model (with half-sinusoidal arcs) are compared with the data from the M5 model (rectangular model). In the second section, the effects of the glottal angles and diameters on the flow contractions will be discussed.

#### 6.3.1 Comparison between M5 and M6

This section compares the M5 and M6 results to show the significance of the three-dimensional effects on the secondary flows. The flow is two-dimensional in a rectangular glottis, and therefore significant components of velocities are only in the coronal cross-sections, and the flow is studied in the $x$-$y$ plane. The main velocity component is the axial velocity (i.e., $x$-velocity), corresponding physiologically to the upward (inferior-to-superior) direction. The M6 glottis has a half-sinusoidal arc on each side, and the anterior-posterior component of the velocity ($z$-velocity) cannot be neglected. This component is responsible for secondary flows in the three-dimensional glottis.
In the M5 model the pressures were actually measured using two staggered rows of seven taps each, located 15 mm (i.e., 0.2 cm, real-life) on either side of the mid-coronal plane. This was possible due to the two-dimensionality of the flow in the rectangular model. It was assumed that the end effects were not important because of the large anterior-posterior distance vs. glottal diameter ratio. However, M6 vocal folds were manufactured to reproduce the rectangular glottal geometry of M5. The tests (not reported here) have indeed reproduced the M5 data on all three rows of 14 taps, which supports the assumption that the wall pressures in a rectangular model do not change along the anterior-posterior diameter.

Based on the flow visualizations in the mid-sagittal plane downstream of the model vocal folds (see Chapter 4), secondary flow in the z-direction causes a difference in pressures in the middle, anterior (1/4), and posterior (3/4) locations. Such a flow pattern was not observed in the M5 model. Figure 6-4 shows computational results in the mid-sagittal plane for an M5-type rectangular geometry (Fig. 6-4a) and for M6 (Fig. 6-4b), for a transglottal pressure of 0.981kPa (10 cm H\textsubscript{2}O). The M5 streamlines are straight with only negligible end effects that become visible only after glottal exit, while for the M6, the deviation of the streamlines is obvious. The last row of plots in Fig. 6-4 show the contours of z-velocity (i.e., velocity in the anterior-posterior direction) for the rectangular M5 model and M6. The magnitudes of the z-velocity in M5 are $|v_z(\text{max})|=1.6$ m/s, compared to $|v_z(\text{max})|=8.1$ m/s in M6.

### 6.3.2 Secondary flow in model M6

This section compares the results of the cases with different glottal angles and diameters to show the significance of the glottal angle effects on the secondary flows. Figure 6-5 presents the velocity profiles in the anterior (1/4) / posterior (3/4) symmetry plane of the 10° convergent glottis, at three axial locations: $x = 0$ cm (i.e., glottal entrance), 0.1 cm, and 0.2 cm (just before the exit rounding of the vocal folds), for a
Figure 6-4: Results of FLUENT simulations in the mid-sagittal section (transglottal pressure 0.981 kPa or 10 cm H₂O). The first row depicts the mid-coronal section (for reference). The middle row shows the total pressure contours and also streamlines. The last row shows contours of z-velocity (i.e., velocity in the anterior-posterior direction). The red and blue color levels correspond to +8 and -8m/s, respectively. Column (a): M5 model (uniform rectangular geometry, glottal diameter of 0.16 cm); Column (b): M6 model (uniform sinusoidal glottis, glottal diameter of 0.16 cm).
transglottal pressure of 0.981 kPa (10 cm H₂O). This anterior-posterior velocity is zero at the mid-coronal section (because of the symmetry across the mid-coronal plane), but in the anterior (1/4) and posterior (3/4) sections the magnitude of this velocity is significant, approximately 3.2 m/s for the glottal entrance, increasing downstream to 3.6 m/s. This velocity within the glottis toward the center of the glottis represents approximately 10% of the magnitude of the axial velocity out of the glottis in the midsection. Higher velocities occur near the anterior and posterior extremities of the glottis.

Figure 6-6 shows qualitatively the velocity vectors in a transverse section of the three models (convergent, uniform, divergent) at the glottal exit; here the case for a transglottal pressure of 0.981 kPa (10 cm H₂O) is presented for illustration. It can be observed that the velocity profiles are relatively uniform across the glottis up to about 0.4 cm from the midsection, and become increasingly non-uniform toward the extremities. The observations above indicate that three-dimensionality of the flow is significant, despite the apparently large aspect ratio (i.e., 7.5) of the anterior-posterior length to glottal diameter. Consequently, the velocity vectors in the mid-sagittal section are oriented toward the mid-coronal (symmetry) plane, as shown in Fig. 5-8. The streamlines indicate that separation occurs at the anterior and posterior ends. The separation occurs upstream of the glottal exit for the uniform and divergent geometries, and slightly downstream of the exit for the convergent geometry.

The flow contraction also was observed even for the smallest diameter case (see Chapters 4, and 5). The streamlines of Fig. 5-24 indicate that separation occurred at the anterior and posterior ends, upstream of the glottal exit, for all three cases, and that the secondary cross flow effect relative to extension toward the center of the glottis was greater with the smallest diameter (also see Fig. 5-18, Fig. 5-31, and Fig. 5-32). Thus, the faster-growing viscous boundary layer at the anterior and posterior ends with decreasing glottal diameter created greater three-dimensionality.
effects of the flow. This action is consistent with elliptical jets, which model M6 can be categorized as. The downstream contraction would be accompanied by flow axis shifting in which the jet switches its major and minor axes as it moves downstream, as has been seen in the flow of phonating excised larynxes by Khosla et al. [19], with similar downstream flow contractions.
Figure 6-5: Anterior to posterior velocity profiles in the midsagittal plane of the M6 10° convergent glottis, at three axial locations: $x = 0$ cm (i.e., glottal entrance), 0.1 cm and 0.2 cm. The transglottal pressure is 0.981 kPa (10 cm H$_2$O).
Figure 6-6: Velocity profiles in a transverse section located at the glottal exit ($x=0.3$ cm), for a transglottal pressure of 0.981 kPa (10 cm H$_2$O), for all three geometries: 10° convergent, 0° uniform, and 10° divergent. The dotted lines trace the projected minimal glottal perimeter.
Chapter 7

Conclusions

This study dealt with the aerodynamics of the airflow passing through a model of the human larynx. Prior studies in the phonation field have typically investigated the more simple rectangular model of the glottis where the flow within the glottis is considered two-dimensional; therefore, only the midcoronal plane of the glottis was necessary to study. Because the glottis has a three-dimensional geometry in reality, the results of the 2D models could be considered as initial approximations, but not sufficiently accurate for a comprehensive study. Of strong interest in voice science is how the pressure distributions in a more realistic (3D) glottis vary in the inferior-superior and anterior-posterior directions for different glottal angles and diameters, and how the pressure distributions change with and without the eccentricity created by the arytenoid cartilages. Therefore, a static model of the larynx with curved vocal fold medial surfaces (called the M6 model) was built in order to perform these tasks.

Model M6 is an empirical static model through which air flows at a constant rate to obtain detailed pressure distributions on the vocal fold surfaces. These distributions act as driving pressures during phonation when applied to multimass analytic computer models, and can be used to test the pressure and flow accuracies of computational models. This model has more realistic (half-sinusoidal) vocal fold surfaces.
and allows investigation of the pressure differences along the anterior-posterior direction with three pressure tap lines at the middle, anterior (1/4), and posterior (3/4) locations. Three pairs of the vocal folds were made to investigate the effects of different glottal angles on the intraglottal pressures, namely, 10° convergent (C16), 0° uniform (U16), and 10° divergent (D16), all with the glottal diameter of 0.16 cm. In order to determine the effects of different glottal diameters on glottal aerodynamics, two additional pairs of vocal folds were built with glottal diameters of 0.04 cm (U04) and 0.01 cm (U01), with the glottal angle of 0° (uniform). For each case, transglottal pressures of 0.294, 0.491, 0.981, 1.472, 1.962, and 2.453 kPa (i.e., 3, 5, 10, 15, 20, and 25 cm H$_2$O) were used. This model could include an arytenoid cartilages structure with no posterior glottal gap, which allowed investigation of the effects of flow eccentricity on the intraglottal pressures and glottal flows. The false vocal folds were not included in this study.

Most applicable methods in fluid mechanics problems are experiments, numerical simulations, and flow visualizations, all of which have been used in this study to accurately obtain more inclusive results. The empirical pressures were compared to computational results obtained with the CFD software package FLUENT. In addition, flow visualizations were conducted using a laser sheet and seeded airflow to study the flow patterns exiting in the glottis. The conclusions in this chapter will be presented in two sections. The first section deals with the effects of the half-sinusoidal arcs of the glottis on the intraglottal pressures and flow fields within the glottis for different glottal angles and diameters. The second section presents the effects of the arytenoid cartilages on the intraglottal pressures and flow fields.
7.1 Half-sinusoidal-arcs Glottis

7.1.1 Pressure gradients

The glottis with half-sinusoidal arcs made a difference relative to intraglottal pressures at the anterior (1/4), middle, and posterior (3/4) planes. The amount of the difference varied based on the glottal angle and diameter. For the cases with the same glottal diameters (0.16 cm) and different glottal angles, the values of the pressure differences did not rise above about 7\% of the transglottal pressure. The mid-location pressures tended to be lower for the convergent (C16) and divergent (D16) cases near glottal entry, but similar for the uniform case (U16) at entry, and about the same within the glottis after an axial distance of about one-third into the glottis. Thus, near the glottal entry, slightly less vocal fold “push” (convergent) and slightly more “pull” (divergent) may exist at the midsagittal plane, compared to locations anteriorly and posteriorly. This conclusion is supported qualitatively by dynamic glottal pressures within an excised hemilarynx canine model given in Alipour and Scherer [4].

Also, for the cases with the same glottal angle (i.e., 0° uniform) and different glottal diameters, the pressures on the medial vocal fold surfaces differed between the midcoronal pressure distribution and the anterior (1/4) and posterior (3/4) positions. For the diameters of 0.01 cm (U01) and 0.04 cm (U04) uniform cases, the pressures along the midcoronal surfaces were less than at the other two locations, suggesting bidirectional pressure gradients in the glottis along the anterior-posterior direction (as seen also in Alipour and Scherer [4]), with more pressure pushing the vocal folds in an outward direction away from the midcoronal plane. The pressure difference was greatest near the glottal entrance, but did not exceed 6.4\% of the transglottal pressure.

The airflow passing the glottis was laminar for a short distance, and the length of the laminar core was higher in the midcoronal plane than the anterior (1/4) and
posterior (3/4) planes for all cases. The laminar core decreased by changing the glottal angle from 10° divergent to 10° convergent, and it also decreased by decreasing the glottal diameter and increasing the transglottal pressure.

7.1.2 Flow fields

For the cases with different glottal angles, the axial velocities in off-center coronal sections were similar to the mid-coronal section axial velocities (being only about 1-4% higher). On the other side, the magnitude of the center-directed velocity in the off-center sections was significant, being on the order of 10% of the main (axial) velocity in the investigated sections (i.e., anterior (1/4) and posterior (3/4) sections). These secondary flows that move toward the center from the more anterior and posterior positions observed in this study are also supported by non-axial exit flow contractions shown in some PIV images in Khosla et al. [19] and observed (and recorded) here. These significant secondary cross flows within the glottis and associated contraction of the flow downstream of the glottis in the sagittal plane were consistent with elliptical jets with axis shifting (as seen also in Khosla et al. [19]). This finding needs to be taken into consideration when the false vocal folds are included in the modeling.

For the cases with different glottal diameters, velocities within the glottis were similar in the anterior-posterior direction for the two larger diameters but differed meaningfully for the smallest diameter, suggesting that multimass models of phonation with multiple anterior-posterior channels should consider velocity changes as a function of diameter and transglottal pressure when calculating the volume flow through each of the channels. Flow skewing occurred for the smallest diameter case (0.01 cm, least wall curvature), but not for the other two diameters (0.04 cm and 0.16 cm) due to high aspect ratios of the glottis and low flows. This suggests that less skewing occurs with greater wall curvature and larger flows. The skewness angle was higher at the anterior (1/4) and posterior (3/4) planes than at the midcoronal plane,
and by increasing the transglottal pressure, the skewness angle of the flow decreased.

Bistable flow skewing downstream of the glottis is prevalent in two-dimensional rectangular glottal models (Erath and Plesniak [12]; Scherer et al. [38]). However, the results here suggest that the half-sinusoidal vocal fold curvature reduces the tendency to skew the flow, except for small diameters. For the smallest diameter case, 0.01 cm, the flow skewed downstream of the glottis, and did so perhaps due to the large aspect ratio of glottal length to midcoronal diameter of 120 (i.e., 1.2 cm / 0.01 cm) and relative low flow rates (and thus less axial momentum of the flow).

A generalization of these results from the 3D laryngeal model M6 to the dynamic human larynx is that there are pressure and velocity gradients in both the axial (upstream-downstream) and longitudinal (anterior-posterior) directions, with primary gradients axially and secondary gradients longitudinally. The A-P gradients typically are bi-directional, with the lowest pressure at the midcoronal location. However, these gradients are strongest for smaller diameters.

### 7.2 Eccentricity

#### 7.2.1 Pressure gradients

Although the eccentricity of the glottis (arytenoid structure) did not change the intraglottal pressures for the two smallest glottal diameters (U01, and U04), for the cases with the largest glottal diameter (0.16 cm) the pressures at the anterior (1/4) and posterior (3/4) planes were not identical. The values of the pressure differences rose for all three cases, but the maximum rise occurred for the 10° divergent case, about 8% of the transglottal pressure. Similar to the cases without the arytenoid structure, the midcoronal pressures were lower for the divergent (D16) and convergent (C16) case near the glottal entry. Contrary to the non-eccentric uniform case (U16), the pressures with the arytenoid structure for all three planes were different.
at the glottal entry (with the highest at the posterior (3/4) plane and lowest at the anterior (1/4) plane) and about the same within the glottis (taps #7-9) at the middle and posterior (3/4) planes. Thus, existence of the arytenoid cartilages caused the asymmetry of the pressure distributions along the anterior-posterior direction for U16.

7.2.2 Flow fields

The M5 (rectangular model) streamlines were straight within the glottis with negligible end effects, while, for M6, the deviation of the streamlines is obvious. The flow contraction, seen for all non-eccentric cases, was created due to the half-sinusoidal arcs of the vocal folds. In addition to the flow contraction, the flow streamlines passing the arytenoid cartilages for the eccentric cases bent toward the midcoronal plane and made extra forces to contract the flow only in the lower half of the glottis length (from the posterior end to the midcoronal plane). Similar to the pressure gradients, the flow fields in both the coronal and sagittal planes for the two lower glottal diameter cases (U04, U01) did not change for the eccentric and non-eccentric conditions. Only for the highest glottal diameters with different glottal angles (C16, U16, and D16) did the flow boundary layer grow faster in the posterior end and the separation points occur earlier within the glottis for the eccentric cases rather than non-eccentric geometries. Also it was observed that, since the flow passing the glottis contracted toward the midcoronal plane, the superior curvature of the arytenoid cartilages did not affect the flow pattern downstream of the glottis; however, more realistic arytenoid geometry (including open posterior glottal gaps) should be considered.

Similar to the coronal view, the airflow passing the glottis was laminar for a short distance in the sagittal view. The length of the laminar core decreased by changing the glottal angle from 10° divergent to 10° convergent. The length of the laminar core also decreased by decreasing the glottal diameter. In the sagittal view also, by
increasing the transglottal pressure, the contraction angles and laminar core lengths both decreased. The thickness of the boundary layer was similar at the anterior and posterior ends for non-eccentric cases. For the eccentric cases, the anterior thickness was less than the posterior thickness due to the flow circulations. By increasing the transglottal pressure, the boundary layer thicknesses decreased in all cases at both anterior and posterior ends.

The current study of the more realistic half-sinusoidal model of the glottis suggests that results from the rectangular models are to be considered carefully. Greater attention needs to be given to the 3D dynamics shaping of the glottis to continue to determine which glottal shapes are realistic and should be studied for their aerodynamics. The more realistic, non-rectangular laryngeal geometries are required in research programs of basic laryngeal function to establish benchmark empirical data.
References


velocity in the in vivo canine laryngeal model with variable nerve stimulation. 


Appendix A

Dynamic Similitude

The experimental study of the larynx is one of the situations in the mechanical engineering that using the real size model is inconvenient due to existing restrictions. Since the real size vocal folds (1.2 x 1.6 cm) are too small to insert 42 pressure taps, scaled up model and similitude concept have been used in this study. Based on similitude technique, it is assumed that the model and prototype are similar in the geometry, kinematic, and dynamic aspects. The geometric similitude requires all the dimensions of the model are equal to real piece dimensions multiplied by a scale factor:

$$\frac{L_M}{L_{RL}} = S_F$$

(A.1)

where $L_M$ and $L_{RL}$ are corresponding dimensions in the model and real-life, respectively. The same concept could be used for area and volume consequently:

$$\frac{A_M}{A_{RL}} = S_F^2 \quad \text{and} \quad \frac{V_M}{V_{RL}} = S_F^3$$

(A.2)

where $A_M$, $A_{RL}$, $V_M$, $V_{RL}$ are corresponding areas and volumes in the model and real-life, respectively. The kinematic similarity requires the ratios of the velocities and accelerations are constant. The dynamic similitude requires that Reynolds number
(Re) and pressure coefficient ($P^*$) are equal in the model and the real-life in order to have the same flow physics. Thus:

$$Re_M = Re_{RL} \Rightarrow \frac{U_M L_M}{v_M} = \frac{U_{RL} L_{RL}}{v_{RL}}$$  \hspace{1cm} (A.3)

The kinematic viscosity, $v$, is unique for both model and real-life (air), which leads to the following equation between the velocities of model and real-life:

$$U_M = U_{RL} \left( \frac{L_{RL}}{L_M} \right) = \frac{U_{RL}}{S_F}$$  \hspace{1cm} (A.4)

The volumetric flow rate will be:

$$Q_M = U_M A_M = \left( \frac{U_{RL}}{S_F} \right) (S_F^2 A_{RL}) = S_F Q_{RL}$$  \hspace{1cm} (A.5)

The pressure coefficient will be:

$$P_M^* = P_{RL}^* \Rightarrow \frac{\Delta p_M}{\frac{1}{2} \rho_M U_M^2} = \frac{\Delta p_{RL}}{\frac{1}{2} \rho_{RL} U_{RL}^2}$$  \hspace{1cm} (A.6)

The fluid is air for both model and real-life and density is the same, thus:

$$\Delta p_M = \Delta p_{RL} \left( \frac{U_M^2}{U_{RL}^2} \right) = \frac{\Delta p_{RL}}{S_F^2}$$  \hspace{1cm} (A.7)

In this study, scaled up model is 7.5 times larger than the real life piece, therefore:

$$S_F = 7.5 \Rightarrow L_{RL} = \frac{L_M}{7.5}$$  \hspace{1cm} (A.8)

$$A_{RL} = \frac{A_M}{7.5^2} = \frac{A_M}{56.25}$$  \hspace{1cm} (A.9)
\[ U_{RL} = 7.5 \, U_M \]  \hfill (A.10)

\[ Q_{RL} = \frac{Q_M}{7.5} \]  \hfill (A.11)

\[ \Delta p_{RL} = 56.25 \, \Delta p_M \]  \hfill (A.12)

All the experimental and numerical values of the model have been measured and computed and then, based on these equations, the correspondence values of the real-life vocal folds have been calculated and depicted in the graphs and tables.
Appendix B

Pressure transducer calibration

As Fig. 2-10 shows two low pressure transducers which used in this study were precisely calibrated. To calibrate these pressure transducers, a highly accurate micro-manometer (see Fig. B-1) used in a circuit accompanied with a pressure generator and two digital voltmeters. Each pressure transducer connected to its own signal conditioner to avoid any mismatching error. The pressure generator output connected to micro-meter and pressure transducer at the same time. For each pressure transducer, different gains (from 0.1 to 1) and different pressures (from 0.294 to 2.453 kPa) were applied and correspondence Pressure-Voltage graphs with their regression line were plotted. The specifications of the Fig. B-2 used to measure the flow rate (PT0) by rotameter and correspondence specifications of the Fig. B-3 applied in Labview program to measure the pressure values (PT1) in each tap locations.
Figure B-1: The calibration setup of the pressure transducers
Figure B-2: Pressure-Voltage graph of PT0 (Flow meter)
Figure B-3: Pressure-Voltage graph of PT1 (Pressure meter)
Appendix C

M6 Labview code

Figure C-1 shows partially the Labview code designed specially for M6 model. The LabVIEW software is a graphical programming environment to develop measurement, test, and control systems using intuitive graphical icons and wires that resemble a flowchart. It offers integration with hardware devices for analysis and data visualization.

The type of data acquisition card (DAQ, model NI USB-6221) which used in this study is capable of controlling the external devices through the digital output. This ability helped to define different steps of the data acquisition procedure like home positioning, start, step forward and waiting time of the pressure scanner valve. It also helped to manipulate the acquired data and write them in a proper format in the output file. In the M5 model all the procedure has been done manually which may introduce the human errors in the procedure.
Figure C-1: The M6 Labview code