European Journal of Mechanics / B Fluids 72 (2018) 23–37

Contents lists available at ScienceDirect

European Journal of Mechanics / B Fluids

journal homepage: www.elsevier.com/locate/ejmflu

Effects of glottis motion on airflow and energy expenditure in a human upper airway model

Jinxiang Xi [a,b,*], Xiuhua April Si [b], Haibo Dong [c], Hualiang Zhong [d]

[a] School of Engineering and Technology, Central Michigan University, 1200 South Franklin Street, Mount Pleasant, MI 48858, USA
[b] Department of Mechanical Engineering, California Baptist University, Riverside, CA, USA
[c] Department of Mechanical and Aerospace Engineering, University of Virginia, Charlottesville, VA, USA
[d] Department of Radiation Oncology, Henry Ford Health System, Detroit, MI, USA

ARTICLE INFO

Article history:
Received 24 August 2017
Received in revised form 13 December 2017
Accepted 23 April 2018
Available online 5 May 2018

Keywords:
Larynx
Glottal aperture
Glottis motion
Cyclic flow
Vortex shedding
Pharyngeal wall collapse

ABSTRACT

The periodic movement of the glottal aperture during tidal breathing has been long recognized as a physiological factor in regulating the respiratory airflow dynamics. However, studies of the dynamic glottis and its functions are scarce due to the complex respiratory anatomy, lack of glottis kinematics, and challenges in simulating moving structures. The objective of this study is to numerically investigate the influences of the glottis motion on airflow features and energy expenditure in an image-based human upper airway model. To examine the relative importance of glottal motion and tidal breathing, both static and dynamic glottal apertures were considered using large eddy simulation under either constant or sinusoidal breathing profiles. The glottis was specified to move in phase with the inhalation profile, which widens and contracts periodically at an amplitude typical of a human adult. Results show highly oscillating features of the instantaneous main and secondary flows for all breathing scenarios considered, indicating the inadequacy of time-averaged steady simulations in dynamic respiratory studies. The glottal aperture and cyclic flow both modified the laryngeal jet instability and vortex generation by varying the main flow speed. However, the cyclic flow has a greater impact on the main flow instability (streamwise direction), while the glottal motion has a greater impact on secondary flows (transverse direction) associated with swirling flows, flow separation, and vortex shedding. A widening glottis during inhalation was observed to significantly postpone the development of vortices, flow oscillation, and intra-glottal pressure drop, which might have key biological implications in alleviating the diaphragm muscle effort and reducing the risk of pharyngeal wall collapse.

1. Introduction

Glottis, which is the aperture between the vocal folds in the larynx, is one of the minimal airflow passages in the human upper airway. It is a major source of flow instabilities and turbulence resultant from the formation of localized eddies. The glottal aperture varies in size and shape with time during respiration or phonation, yielding a complex time-varying jet-like tracheal flow [1]. While the glottal motion was extensively explored in human phonation, studies of glottal motion during respiration are scarce. Most respiratory studies, if not all, had assumed a static glottis in the context of breathing or inhalation dosimetry, thus neglecting the flow uncertainties related to the glottis motion. This neglect was presumably attributed to three factors: the lack of *in vivo* measurements of glottis kinematics, the numerical complexity in simulating moving structures, and the technical challenges in rendering anatomically accurate respiratory structure. However, with the advances in computation and imaging technologies, all of the three obstacles have been greatly mitigated. It becomes feasible to quantitatively characterize the role of the dynamic glottal aperture on flow dynamics, vortex topologies, and breathing resistance in physically realistic airway models under *in vivo*-like breathing conditions.

Several *in vivo* studies measured the glottal cross-sectional area and its variation during the breathing cycle. D'Urzo et al. [2] measured the glottal area of 11 subjects at functional residual capacity using both CT scanning and acoustic reflection methods. The glottal area varied in the range of 40–290 mm^2 with the mean value being 180 mm^2. A similar mean value of 170 mm^2 was reported by Martin et al. [3] from 114 subjects. Considering the gender difference, Rubinstein et al. [4] reported a glottal area of 144–211 mm^2 for males and 137–207 mm^2 for females during deep breathing. Scheinherr et al. [5] measured the glottal areas in 20 subjects using nasofibroscopy and reported the peak value of

* Corresponding author at: School of Engineering and Technology, Central Michigan University, 1200 South Franklin Street, Mount Pleasant, MI 48858, USA.
E-mail address: jxi@calbaptist.edu (J. Xi).

https://doi.org/10.1016/j.euromechflu.2018.04.011

217 ± 54 mm^2 (mean±SD) during inspiration, and 178 ± 35 mm^2 during expiration. Different amplitudes of glottal motions were observed. Those with a glottal area variation smaller than 10% during a breathing cycle were categorized as "static", while those larger than 10% were "dynamic". The "static" glottis during respiration has been previously reported in 1 subject out of 3 [6]. The dynamic glottis is featured by a progressive widening during inhalation, with the peak glottal area being 1.26–1.46 times that of the minimal value. Different results of the peak-minimal area ratio had been reported, for instance, to be 1.8 by Brancatisano et al. [1] and 1.16–1.54 by England et al. [7] In addition, it was observed that the amplitudes of glottal motion were greater in females than males [5].

In addition to the dynamic glottis, tidal or cyclic breathing is another intrinsic feature of human breathing. An accurate understanding of the respiratory dynamics requires that the inhalation flow profile imitates that occurring *in vivo*. Under cyclic flow conditions, the glottis-induced flow instabilities can be further complicated by the continuous acceleration and deceleration of the air as well as by the active fluid–structure interactions. Large differences are issued in airflow distribution and inhaled particle deposition between constant and cyclic flows [8,9]. Increased vorticity may also result from cyclic flows [10]. Nonetheless, how the cyclic flow and dynamic glottis, individually or as a group, affect the airflow and resistance, and to what level, still is not clear.

Some experimental and numerical studies have investigated the impacts of the glottal motion and cyclic breathing on respiratory flow dynamics. Katz and Martonen [11,12] studied the laryngeal flows in both replica casts and computational models and emphasized the importance of the glottis on the flows in the trachea. KatChoi and Wroblewski [13] empirically investigated the glottis-induced turbulence for oscillatory flows in an idealized larynx–trachea cast by employing anemometry measurement and smoke-wire visualization techniques. Turbulence intensities for the triangular aperture case were observed to differ significantly from those for the circular case. Renotte et al. [14] simulated the main and secondary flows in a straight channel with variable constriction levels. A backflow and a double pair of vortices were captured downstream of the glottal constriction. Based on the quasi-steady assumption, the cyclic flow was modeled using a succession of 14 steady simulations in place of a transient simulation [14]. Cui and Gutheli [15] simulated the inspiratory flow at a constant flow rate using large eddy simulations and reported different sizes of vortical flows as opposed to the symmetric double pair of counter-rotating vortices that characterized time-averaged flow field. Brouns et al. [16] numerically evaluated the effects of glottal size and shape on flow behaviors in a 3D idealized mouth–throat model with a static glottis of different shapes: circular, elliptical, and triangular. It was observed that the triangular glottis shifted the laryngeal jet to the back wall and induced two pairs of vortices in the subglottic region, while the circular or elliptical glottis did not significantly alter the laryngeal jet and generated one pair of vortices only. In addition, the flow resistance is more dictated by the area than the shape of the glottis [16]. The above study also called for more realistic image-based airway models, life-situation glottis kinematics, and accompanied cyclic inhalation flow rate in future studies.

In summary, static glottis and steady or quasi-steady flows have often been assumed in previous *in vitro* and numerical works. The objective of this study is to quantify how the glottis motion and cyclic flow affect the respiratory dynamics individually or as a combination. Specific aims include: (1) developing a computational airway model with a time-varying glottal aperture, (2) characterizing the effects of glottis motion and cyclic breathing on flow and vortex topologies, (3) quantifying the shear stress, flow resistance, and inspiratory effort among different breathing conditions, (4) exploring the mechanisms of the glottis motion and cyclic flow in regulating respiratory dynamics.

2. Materials and methods

2.1. Study design

To assess the influences of tidal breathing and dynamic glottis on airflows, four breathing scenarios were examined, as shown in Fig. 1. Only inhalations were simulated in this study. The flow rate was specified to approximate quiet breathing conditions (15 L/min), which is equivalent to the flow rate during sleep [17]. The inhalation profile was specified to be either constant or following a sinusoidal waveform. Similarly, the glottal aperture was specified to be either rigid (static) or varying in phase with the inspiratory flow (dynamic). Four combinations of breathing scenarios were planned: (1) a constant flow rate and a rigid glottis (constant–rigid), which represents the most idealized model in predicting respiratory flows, (2) a constant flow and a dynamic (expanding) glottis (constant–dynamic), which approximates the respiratory flows during quasi-steady inhalation but excludes the effects from flow development, (3) a sinusoidal flow and a rigid glottis (sine–rigid), which represents the *in vivo* condition in subjects with paralyzed glottis, and (4) a sinusoidal flow and a dynamic glottis (sine–dynamic), which aims to approximate the *in vivo* condition for healthy subjects. By comparing Case 1 and 2 (or Case 3 and 4), the influence of glottis motion can be assessed. Similarly, by comparing Case 1 and 3 (or Case 2 and 4), the influence of flow unsteadiness can be gauged. Furthermore, the differences between Case 1 and 4 will give clues on how current numerical practice underestimates the life condition.

We first developed a mouth–lung geometry model with controllable glottal apertures. User-defined modules were written to control the glottis motion and cyclic breathing. We then validated the computational model by comparing predicted pressures to *in vitro* measurements. The validated computational model was subsequently implemented to predict the airflow and vortex topologies under the four breathing scenarios.

2.2. Computer model of upper airway with dynamic glottal apertures

An anatomically accurate mouth–lung model that had been previously developed [18] was used in this study. This model geometry was a combination of two components: a mouth–throat model and a tracheobronchial (TB) model that extended to G6 (Fig. 1). The mouth–throat model geometry was reconstructed from CT images of a 53-year-old adult [19]. The TB geometry was reconstructed from CT scans of a hollow lung cast, which has originally been developed from a cadaver of 34-year-old male [20]. Totally, 44 bronchi and 23 outlets were retained in the TB model. Considering the airway complexity, unstructured elements were generated via ANSYS ICEM CFD (ANSYS, Inc.). To resolve the large gradients within the boundary layer, a body-fitted mesh was developed with fine prismatic cells near the wall.

The kinematics of the glottal aperture was adopted from the measurements by Scheinherr et al. [5,21] using laryngofibroscopy. The glottis has a wedged shape. The anterior–posterior length of the glottis is an average of a group of patients [5] and is kept constant in this study. The width of the glottis is assumed to expand during the first half of the inhalation cycle and contracts to its original state during the second half of the cycle [5]. Specifically, the glottis kinematics was prescribed separately on the two side walls of the glottis (vocal folds), with each following a sinusoidal profile: $0.5a[1 - \cos(4\pi t/3)]$. Here, a is the amplitude of glottal motion and the inhalation period is 1.5 s. For tidal breathing, the flow rate was in phase with the glottal motion. In this study, the glottis expansion ratio is 1.6, with the original area being 96.5 mm^2 and the maximal area being 153.7 mm^2, as displayed in Fig. 1(a–d) and Table 2. This expansion ratio falls within the range of 1.16–1.8 reported for normal adults [1,6,7] and was assumed to be