Increasing the complexity of glottal flow models: in-vitro validation for steady flow conditions

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Quasi one-dimensional glottal flow descriptions predict vocal folds oscillations characteristics which are qualitatively relevant to *in-vitro* and *in-vivo* experimental data. The current paper considers the resolution of the 2D Navier-Stokes equations in order to obtain a refined description of the flow phenomena adapted to more realistic glottal geometry. The pressure and flow rate predictions obtained from quasi one-dimensional flow models and the resolution of the 2D Navier-Stokes equations are examined for steady flows within a rigid glottis. The models predictions are validated against *in-vitro* measurements performed on rigid constriction replicas comparable to the geometrical conditions of the glottis and mounted in a suitable set-up. The confrontation between the experimental and computed data tends to show that the accuracy of the estimated pressures increases with the complexity of the flow model whereas the inverse tendency can be observed for the estimated flow rates. A focus is made on the flow separation point which is predicted by the resolution of the Navier-Stokes equations and appears to be a crucial parameter of the quasi one-dimensional flow models. The use of a variable separation criterion obtained from the 2D flow modeling in the quasi one-dimensional models makes the different models predictions more similar.

1 Introduction

During phonation, the forces exerted by the airflow coming from the lungs on the vocal folds are linked to the pressure drop within the glottis which is driven by the subglottal pressure and depends on the geometrical configuration of the glottal channel. Flow models based on steady Bernoulli's equation and assuming flow separation near the outlet of the glottal constriction allow to provide a physical explanation of the self-sustained oscillating behavior of the vocal folds. Several studies including *in-vitro* experiments show that Bernoulli flow model coupled with simplified lumped models can approximate oscillations characteristics, such as oscillation threshold pressure, to a fair extent [9, 8]. However, Bernoulli flow description implies several assumptions which can lead to drastic approximations irrelevant for glottal flow modeling. The main flow property neglected in Bernoulli flow model is the viscosity of the fluid. Indeed viscous effects can be predominant to determine the flow characteristics especially when the gap between the vocal folds is very narrow [3]. The availability of faster computation facilities made possible glottal flow simulation with more sophisticated models based on the resolution of the two-dimensional Navier-Stokes equations [4]. Therefore CFD techniques allow the study of more complex flow phenomena such as flow separation and jet formation downstream the glottal constriction. More recently, CFD and turbulent flow models have also been used for glottal flow modeling in order to approach the complex reality of the flow behavior in the human upper airways [2]. The choice of the flow model has a major influence on the properties of the oscillating system in physical phonation models. CFD methods provide a more accurate description of the flow but the computation cost is still high and seems not suitable for physical phonation models application such as voice synthesis. In that perspective, quasi one-dimensional flow model represent a trade-off between the computation time and the accuracy of the estimated flow characteristics. Indeed, assuming that the flow properties vary only in one dimension allows to reduce the computations while viscosity and unsteadiness can be taken into account with corrective terms in the Bernoulli flow description. In return, quasi one-dimensional flow models are unable to predict flow separation which is determined by an *ad-hoc* criterion. It has been shown that simplified 1D models can provide realistic predictions compared to *in-vitro* flow measurements but their accuracy remains strongly dependent on the choice of the separation criterion [3]. Therefore, it seems interesting to use CFD in order to verify that more advanced flow models improve the accuracy of the predictions. Two-dimensional flow modeling can also be used to determine the separation criterion inherent to the flow models based on Bernoulli's equation.

This paper presents the comparison between simulations of steady laminar flow within a constriction obtained from quasi one-dimensional models and numerical resolution of the two-dimensional Navier-Stokes equations. The validity of the theoretical models predictions is tested against *in-vitro* measurements performed on glottal constriction replicas mounted in a suitable experimental set-up. This study mainly deals with the predictions of the pressure profiles along the constriction walls, and particularly the pressure at the minimum constriction height, and the volume flow rate. Since the determination of these quantities with 1D models depends on the flow separation point, the choice of the separation criterion is discussed. At first, quasi one-dimensional models are formulated and the numerical flow simulations approach is presented. The experimental set-up is then described. Finally, *in-vitro* measurements and the corresponding models predictions are compared and the models accuracy is discussed.

2 One-dimensional flow models

Under the assumptions of one-dimensional, laminar, fully inviscid, steady and incompressible flow, one-dimensional Bernoulli's equation can be used to estimate the pressure within a constriction. For a rectangular glottal geometry with area $A(x) = l_g h(x)$, the pressure profile along the flow direction x can be determined as:

$$p(x) = p_0 - \frac{1}{2}\rho\frac{\Phi^2}{l_g^2}\left(\frac{1}{h(x)^2} - \frac{1}{h_0^2}\right) \qquad (1)$$

where p_0 is the upstream pressure, ρ, the fluid density, Φ, the volume flow rate and h_0, the subglottal height. The volume flow rate is assumed to be constant along the constriction, *i.e.* $\Phi = v(x)A(x) = v(x)h(x)l_g = constant$. Bernoulli law is unable to predict flow separation and turbulent jet formation downstream of the

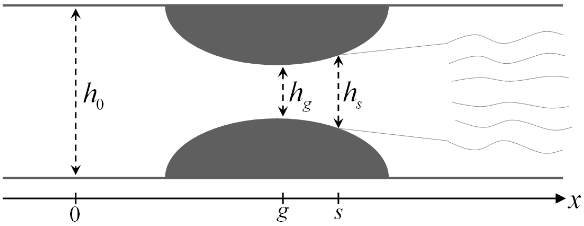


Figure 1: Schematic representation of the glottal geometry. The x-dimension indicates the flow direction. 0, g and s indicate the positions of the origin, minimum aperture and flow separation along the channel. The corresponding heights are indicated.

minimum aperture $A_g = h_g l_g$. This phenomenon resulting from very strong viscous pressure losses [2] must be taken into account in order to predict a pressure drop across the constriction with the one-dimensional Bernoulli equation (1) [7]. In literature, the area associated with flow separation A_s is empirically chosen as 1.1, 1.2 or 1.3 times the minimum glottal constriction area A_g, i.e. $A_s = c_s A_g$ with $c_s > 1$ the *ad-hoc* separation coefficient [6, 5]. For a rectangular area, it is therefore assumed that flow separation occurs at position $x = s$ where the constriction height becomes $h_s = c_s h_g$ as indicated in Fig. 1. Consequently, Eq. (1) only holds down to the separation point after which the pressure is considered equal to the downstream pressure.

Viscous effects also influence the pressure distribution within the constriction, especially for small Reynolds numbers and then can not be neglected for small constriction apertures. In order to account for viscosity, a pressure term is added to Eq. (1) defining Poiseuille model as:

$$p(x) = p_0 - \frac{1}{2}\rho\frac{\Phi^2}{l_g^2}\left(\frac{1}{h(x)^2} - \frac{1}{h_0^2}\right) - 12\mu\frac{\Phi}{l_g}\int_0^x \frac{dx}{h(x)^3} \qquad (2)$$

where μ is the dynamic viscosity of the fluid.

In this paper, one-dimensional flow models (1) and (2) are used to predict the pressure at the minimum constriction height $p_g = p(x = g)$ and the volume flow rate Φ with the pressure difference $p_0 - p_s$, the constriction height profile $h(x)$ and the separation coefficient c_s as inputs.

3 Two-dimensional simulation

Numerical flow simulations in two dimensions have been performed with the software *ADINA CFD* [1].

3.1 Flow model

The equations under consideration are the Navier-Stokes and continuity equations for steady, incompressible, laminar flow. The fluid material used is air with constant thermodynamic and mass transport properties so that the governing equations for the flow domain are expressed as:

$$\rho\,(v \cdot \nabla v) - \mu\nabla^2 v + \nabla p = 0 \qquad (3)$$

$$\nabla \cdot v = 0 \qquad (4)$$

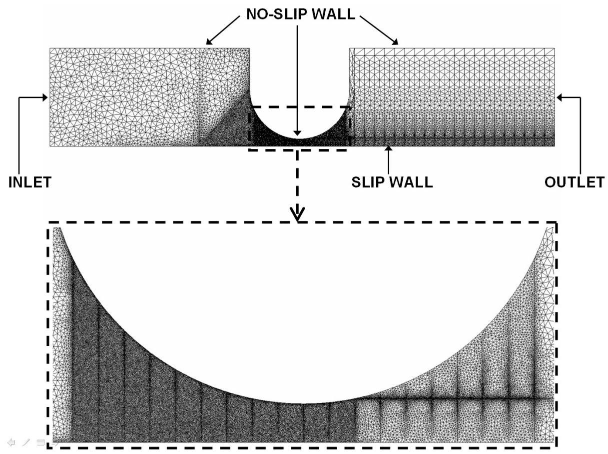


Figure 2: Finite element mesh of the flow domain for the round constriction and h_g=1.5mm. Boundary conditions are indicated.

Finite Element Method (FEM) is used for spatial discretization of the problems which are solved with sparse solver. The flow domain is covered by about 70000 3-nodes planar elements. The mesh is denser in the constriction, and especially along the border walls as shown in Fig. 2, since most of the pressure and velocity variations occur in this part of the geometry. This also allows to have a fine description of the profiles along the wall in order to obtain precisely the flow separation point in the diverging downstream part of the constriction. Though the jet after flow separation should be turbulent, laminar flow model is used since the flow is expected to be laminar in the constriction up to the separation point.

3.2 Boundary conditions

The boundary conditions applied for the geometry description are presented in Fig. 2. No-slip wall condition is used for the walls surrounding the flow domain. The flow problem is considered as symmetric since steady laminar flow model is used. This assumption allows to avoid Coanda effect and forces the jet to be straight. Thus, half of the geometry is modeled and slip wall condition is used for the symmetry line. The inlet pressure is defined with the upstream pressure p_0 and zero-pressure condition is applied to the outlet in order to completely determine the pressure solution.

4 Experimental set-up

The experimental set-up is schematically depicted in Fig. 3. Steady flow is provided by a valve controlled air supply [A] connected to a pressure tank of 0.75 m^3 [B] enabling to impose an airflow through the rigid vocal fold replica [D,E]. An upstream pipe [C] of 95 cm is used to prevent from turbulent flow at the replica position. Pressure transducers (Endevco 8507C or Kulite XCS-093) are positioned in pressure taps upstream of the replica [F] and at the minimum constriction height of the constriction [G] allowing to measure the upstream pressure p_0 and the pressure at the minimum constriction height p_g. The volume flow rate Φ is measured (TSI 4000) upstream of the constriction [H]. The *in-vitro* con-

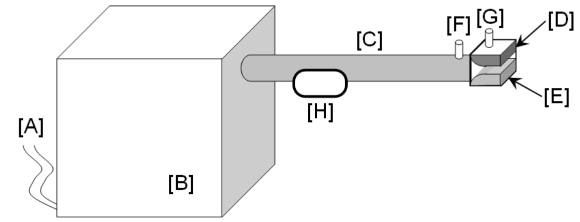


Figure 3: Schematic representation of the experimental set-up: [A] air supply, [B] pressure tank, [C] upstream pipe, [D,E] rigid vocal fold replica, [F,G] pressure taps, [H] volume flow rate meter.

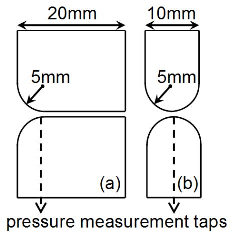


Figure 4: Geometries of the rigid vocal fold replicas. Uniform (a) and round (b) constriction.

striction is formed by two vocal fold metal replicas in a fixed position. The minimum constriction height h_g between the two rigid vocal folds can be changed by means of two adjustment screws. Different minimum constriction heights are studied: h_g=0.2 mm, h_g=0.5 mm, h_g =1.0mm and h_g =1.5mm. Two different constriction shapes depicted in Fig. 4 are considered : (a) uniform (with a rounded entrance) and (b) round, in order to favor either the study of viscous wall effects or flow separation.

5 Results and discussions

5.1 Uniform constriction

A uniform constriction is particularly interesting to evaluate the quasi one-dimensional models performance independently of the choice of the separation coefficient. The channel is indeed straight and flow separation always occurs at the end of the constriction so that $c_s = 1$. As shown in Fig. 5a and 6a, Bernoulli model predicts that the pressure within the uniform constriction is always equal to the downstream pressure regardless the upstream pressure whereas Poiseuille model is able to predict positive pressures p_g at the minimum constriction height. Thus for very narrow gap, as in Fig. 5a, Poiseuille model predictions match quasi perfectly the experimental pressure measurements, with a mean error less than 2%. For this case, 2D flow model predicts the *in-vitro* pressure data with a mean error about 30% and so this more advanced model appears to be less accurate with respect to measurements. For larger apertures, all the models predictions become less accurate, as shown in Fig. 6a. Thus, the mean prediction errors for Poiseuille and 2D models are respectiveley about 60% and 40%. Concerning quasi one-dimensional model, acounting for viscosity appears to be crucial to

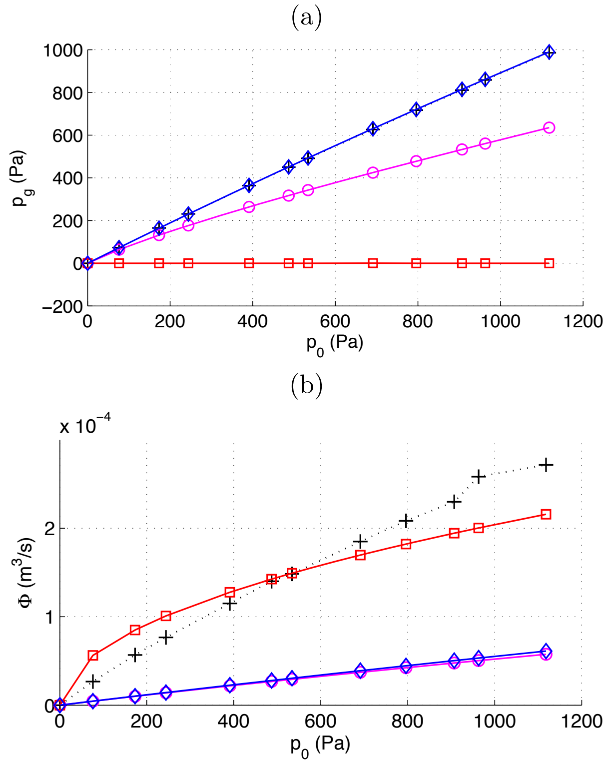


Figure 5: Measurements (+) and models predictions (□, Bernoulli, ◇, Poiseuille, ∘, 2D Laminar) of pressure at the minimum constriction height p_g (a) and volume flow rate Φ (b) for the uniform constriction with minimum constriction height h_g=0.2mm.

approach pressure measurements. For very small apertures, viscous effects become predominant for the determination of the pressure within the constriction so that Poiseuille model is fully capable to predict the measured pressures. The relative error between the pressure measurements and the 2D model predictions appears to always be in the range 30-40% regarless the upstream pressure and the minimum constriction height whereas the relative error observed for Poiseuille model increases as the minimum constriction height increases.
Concerning volume flow rate, Bernoulli model appears to be a good estimator of the measurements. For h_g= 0.2mm, though Poiseuille model is the most suitable to predict the measured pressures, it can only predict the measured volume flow rate with a mean error about 80%, as shown in Fig. 5b, whereas Bernoulli model can predict it within 20%. For this case, the estimations of the volume flow rate from Poiseuille and 2D models are very similar but when the gap becomes larger, Poiseuille model tends to provide predictions closer to the ones of Bernoulli model. As shown in Fig. 6b, quasi one-dimensional models provide estimations of the volume flow rate with less deviation from the experimental data than the ones given by 2D model. Thus, two-dimensional flow model seems to be unable to predict the measured volume flow rate in a suitable way and accounting for viscosity can result in more inaccurate one-dimensional models estimations.

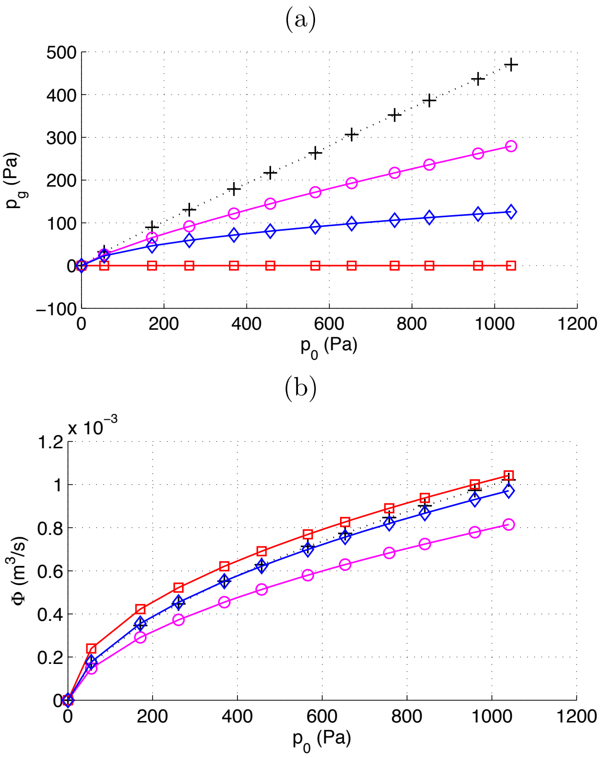


Figure 6: Measurements (+) and models predictions (□, Bernoulli, ◊, Poiseuille, ∘, 2D Laminar) of pressure at the minimum constriction height p_g (a) and volume flow rate Φ (b) for the uniform constriction with minimum constriction height h_g=1.0mm.

5.2 Round constriction

The influence of flow separation can be studied with a round constriction since this geometry includes a diverging downstream part. Fig. 7 and 8 show the measurements and models predictions of the pressure at the minimum constriction height p_g and the volume flow rate Φ for the minimum constriction heights h_g=0.5mm and h_g=1.5mm. The 1D models predictions presented in these figures are computed with $c_s = 1.2$, which is a value commonly found in literature, and c_s given by 2D simulations. One-dimensional models using $c_s = 1.2$ both fail to reproduce the experimental measurements of p_g. The predictions of 2D model are more relevant to the *in-vitro* data but remain inaccurate with mean errors about 50% for h_g=0.5mm and 30% for h_g=1.5mm. In return, as for the uniform constriction, the quasi one-dimensional models predictions of the volume flow rate are closer to the measurements than the ones provided by the 2D model. As shown in Fig. 8b, the 1D models predictions for h_g=1.5mm are very accurate with respect to the experimental data. For narrower gap, they are less accurate but remain better than the predictions of 2D model.

The separation coefficient c_s is a control parameter of quasi one-dimensional models but it can be deduced from the separation position given by 2D simulations. Thus the separation coefficients obtained for different constriction heights are presented in Fig. 9. First, it can be seen that the approximation $c_s = 1.2$ is not valid for small upstream pressure, *i.e.* $p_0 < 50Pa$, or for narrow gap such as h_g=0.2mm. It also appears that the

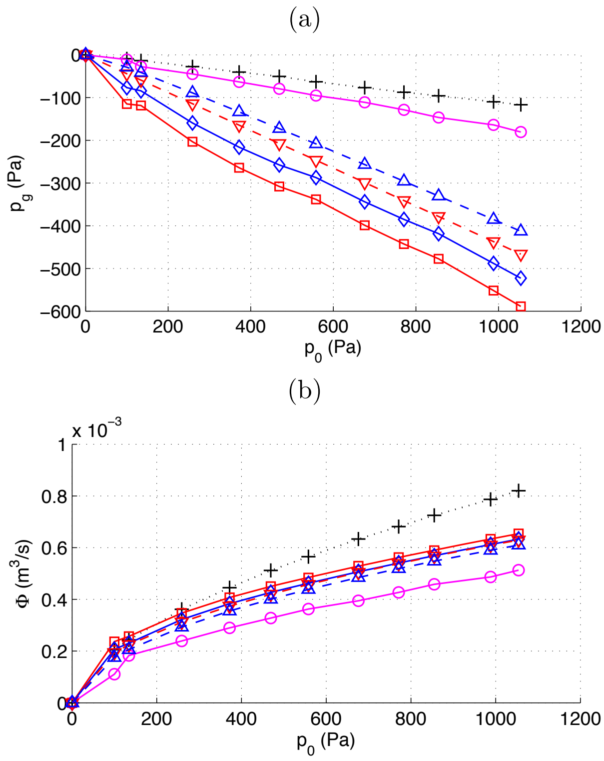


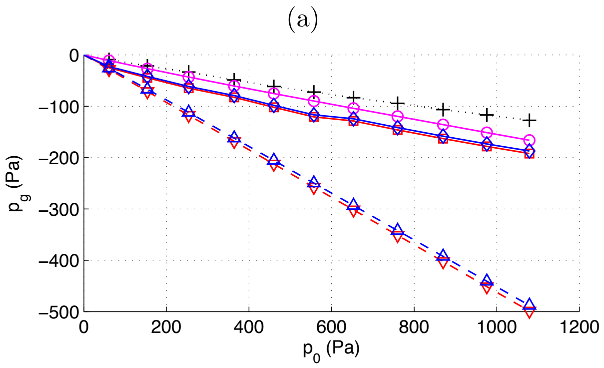
Figure 7: Measurements (+) and models predictions (□, Bernoulli with c_s obtained from 2D model, ◊, Poiseuille with c_s obtained from 2D model, △, Bernoulli with c_s=1.2, ▽, Poiseuille with c_s=1.2, ∘, 2D Laminar) of pressure at the minimum constriction height p_g (a) and volume flow rate Φ (b) for the round constriction with minimum constriction height h_g=0.5mm.

separation coefficient varies from 1.1 to 1.6 for most of the simulated conditions.

Applying the separation coefficient c_s obtained from 2D simulations does not considerably improve neither 1D models predictions for h_g=0.5mm. For h_g=1.5mm, the 1D models predictions of p_g become similar to the ones of 2D model as shown in Fig. 8a. Thus, Poiseuille model is able to predict the experimental measurements within 40%. The 1D models predictions of Φ are also closer to the ones of the 2D model so that they are less accurate.

6 Conclusion

Simplified flow descriptions and numerical simulations are applied to the modeling of airflow within constriction replicas relevant to the glottal flow conditions. Theoretical results are compared to pressure and volume flow rate data obtained experimentally. Despite an error between 30% and 40% relatively to the *in-vitro* pressure measurements, two-dimensional laminar flow model is more accurate than quasi one-dimensional models. The prediction error rate of 2D model remains in the same range regardless the flow and geometrical conditions whereas 1D models can widely overestimate the pressure drop within the constriction. However, Bernoulli flow model appears to best approximate the volume flow rate measurements. The assumption of a varying separation point appears to be more in accordance with the



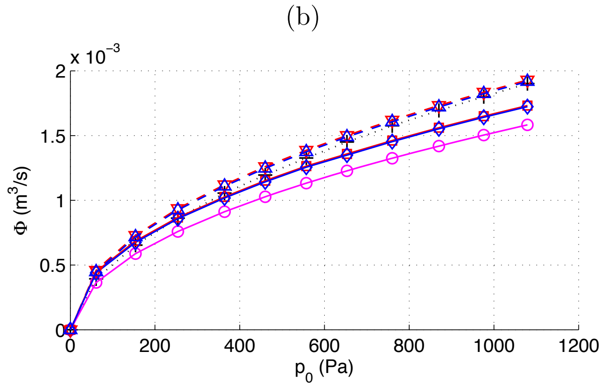


Figure 8: Measurements (+) and models predictions (□, Bernoulli with c_s obtained from 2D model, ◊, Poiseuille with c_s obtained from 2D model, △, Bernoulli with c_s=1.2, ▽, Poiseuille with c_s=1.2, ∘, 2D Laminar) of pressure at the minimum constriction height p_g (a) and volume flow rate Φ (b) for the round constriction with minimum constriction height h_g=1.5mm.

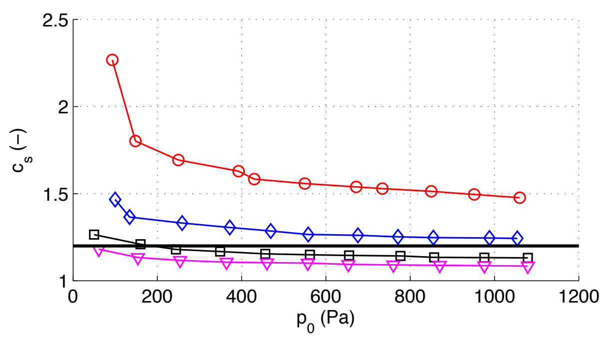


Figure 9: Separation coefficient c_s, obtained from 2D flow simulations, as function of the upstream pressure p_0 for h_g=0.2mm (∘), h_g=0.5mm (◊), h_g=1.0mm (□) and h_g=1.5mm (▽).

physical reality. Then, for 1D flow computations, the separation criterion should be adapted according to the input parameters: the upstream pressure and the minimum constriction height. The use of the separation coefficient obtained by 2D simulation does not necessarily improve the 1D models accuracy with respect to the *in-vitro* pressure measurements. For small minimum apertures (less than 5% of the upstream area), the 2D model's separation coefficient is greater than the common value c_s=1.2 and makes the 1D models pressure predictions less relevant. For larger constriction gap the use of the 2D model's separation coefficient in 1D models results in more similar models results, improving the 1D models pressure predictions accuracy with respect to the experimental data. This paper investigate on flow characteristics within the glottal constriction up to the flow separation point. For a more global study of the glottal flow, turbulent models can be introduced to provide a finer description of the jet formation and its influence on the flow within the constriction. Measurements of additional flow properties, such as velocity profiles, can be envisaged in order to complete the *in-vitro* validation.

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