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ORIGINAL ARTICLE

Experimental validation of quasi-one-dimensional and two-dimensional steady glottal flow models

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Abstract Physical modelling of phonation requires a mechanical description of the vocal fold coupled to a description of the flow within the glottis. In this study, an in-vitro set-up, allowing to reproduce flow conditions comparable to those of human glottal flow is used to systematically verify and discuss the relevance of the pressure and flow-rate predictions of several laminar flow models. The obtained results show that all the considered flow models underestimate the measured flow-rates and that flow-rates predicted with the one-dimensional model are most accurate. On the contrary, flow models based on boundary-layer theory and on the two-dimensional numerical resolution of Navier–Stokes equations yield most accurate pressure predictions. The influence of flow separation on the predictions is discussed since these two models can estimate relevant flow separation positions whereas this phenomenon is treated in a simplified ad-hoc way in the one-dimensional flow modelling. Laminar flow models appear to be unsuitable to describe the flow downstream of the glottal constriction. Therefore, the use of flow models taking into account three-dimensional effects as well as turbulence is motivated.

Keywords Glottal flow modelling · In-vitro measurements · Experimental validation · Flow separation

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1 Introduction

Phonation or human-voiced sound production (e.g. vowels) is due to the vocal fold oscillations within the larynx. It is well established that these oscillations result from instabilities of the fluid–structure interaction between the airflow coming from the lungs and the vocal fold tissues. The improvements brought to the mechanical modelling of the vocal fold tissues, the description of the glottal orifice shape or the modelling of the glottal flow intend to obtain more accurate predictions of physical and physiological quantities associated to phonation, in particular for pathological cases [12]. This development needs to be completed by an experimental approach [26] to evaluate the benefit, in terms of accuracy of the predictions and validity of the assumptions, obtained by using more complex models, especially if the computational cost is taken into account.

The early models proposing a physical description of phonation [11] assume that the glottal geometry is fully characterised by the variation of the glottal channel cross-sectional area and that the glottal flow properties only vary in the flow main direction. Moreover, the position of the flow separation in the downstream part of the glottal constriction is often determined roughly, from an ad-hoc geometric criterion [14], since one-dimensional flow models based on Bernoulli's principle are unable to predict this position. The use of smooth geometries to describe the glottal channel is more relevant to the physiological reality [10] and provides more reliable predictions of the flow separation position based on flow properties [18]. Boundary-layer methods [13] indeed represent a first step in the sophistication of the glottal flow modelling and allow predictions of flow separation positions.

The incessant increase of computational resources enables the emergence of higher dimensional models of the vocal folds and the glottal flow. Fluid–structure interaction systems based on the numerical resolution of the solid and fluid mechanics governing equations on discretised two-dimensional domains were proposed [2, 22] to model the vocal fold motion. For the vocal fold modelling, the application of numerical resolution methods, e.g. finite-element method, allows the definition of a mechanical structure more relevant to the vocal fold physiology. For the glottal flow modelling, the numerical resolution of Navier–Stokes equations allows considering the influence of asymmetries in the glottal channel and yielding more detailed flow properties, e.g. spanwise velocity profiles or the stress exerted on the vocal fold. Three-dimensional models [4] use coarse meshes to reduce the computation cost. This low spatial resolution leads to imprecise predictions of the glottal flow properties, especially regarding the flow separation phenomenon. Representing the vocal fold by a membrane-covered fluid-filled cavity [23] establishes a link between the physical modelling of phonation and several studies concerning collapsible tubes [15, 16]. Besides, finite-element modelling can be used to estimate parameters in more simplified models [5].

In previous studies [6, 7], comparisons are made between the predictions given by one-dimensional, boundary-layer and two-dimensional flow models. The influence of the glottal flow model on the vocal fold mechanical model behaviour is particularly investigated. In these studies, the two-dimensional model is considered as the reference in the predictions comparison. However, since glottal flow is three-dimensional and can develop a turbulent character [17], it is questionable whether two-dimensional laminar flow models could provide an appropriate validation for simpler models.

Therefore, the objective of this study is to carry out a systematical validation of three different laminar flow models, classically applied to glottal flow modelling. This validation is based on an experimental approach in which the pressure and flow-rate predictions provided by one-dimensional, boundary-layer and two-dimensional models are tested against in-vitro measurements performed on glottal constriction rigid replicas [8, 27]. Besides, the strong dependency of the accuracy of one-dimensional models on the choice of the ad-hoc criterion to characterise flow separation was pointed out [3]. Therefore, this study bears a particular interest to the evolution of the flow separation position predicted by more sophisticated models, as function of the imposed geometrical and flow conditions.

2 Methods

2.1 Experimental set-up

In order to experimentally validate the predictions provided by the considered models, the in-vitro set-up depicted in Fig. 1 was used. This set-up includes a glottal constriction replica formed by vocal fold rigid replicas of various shapes. In this study, two shapes were considered. The first shape combines a rounded entrance followed by a uniform cross-section. This shape allows one to avoid the influence of a varying flow separation position on the models predictions since flow separation is forced to occur at the exit of the channel. In the second case, the constriction formed by the rigid replicas has a rounded shape so that flow separation occurs before the exit of the channel. This shape is interesting to study the variations of the flow separation point.

For both uniform and round constrictions, the imposed steady conditions are the following:

- the upstream pressure, $p_0 = p(x_0) = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\} \times 100\,\mathrm{Pa}$
- and the minimum constriction height, $h_g = \{0.2, 0.5, 1.0, 1.5\}\,\mathrm{mm}$.

The other measured quantities are:

- the pressure at the minimum constriction height on both vocal fold replicas, p_g
- and the volume flow-rate, Φ.

Considering the imposed flow conditions and the dimensions of the replicas, the designed set-up reproduces in-vitro conditions relevant to human glottal flow conditions during phonation. A comparison of typical values related to flow within human glottis and in the in-vitro replicas is presented in Table 1, in which Reynolds number Re is defined as

$$Re = \frac{u_g h_g}{\nu} = \frac{\Phi}{\nu\, l_g} \quad (1)$$

and Reynolds number Re_δ, modified to take into account the length and the height of the channel, is defined as

$$Re_\delta = Re\frac{h_g}{L} = \frac{\Phi\, h_g}{\nu\, l_g\, L} \approx \left(\frac{h_g}{\delta}\right)^2 \quad (2)$$

This non-dimensional number can be used to approximate the ratio between the channel height and the viscous boundary layer thickness δ.

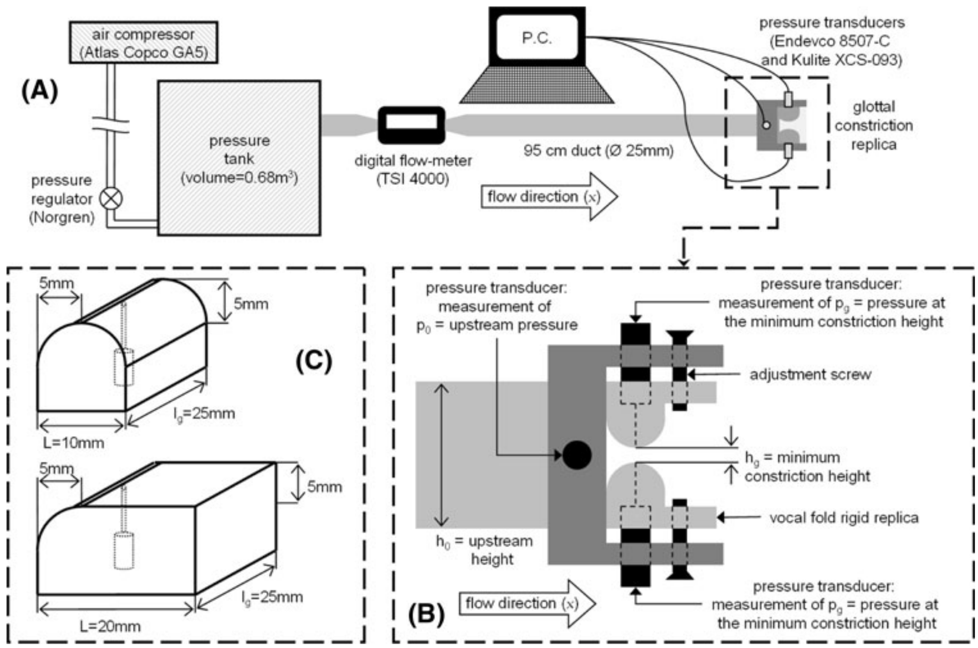

Fig. 1 **a** Schematic representation of the experimental set-up. **b** Schematic representation of the glottal constriction replica. **c** Dimensions of the round and uniform rigid replicas of the vocal fold

Table 1 Comparison between typical values related to flow in the human glottis during phonation [9, 19, 24] and in the in-vitro replicas

Quantity	Symbol	On human	On replicas
Glottal channel length	L	4 mm	10–20 mm
Glottal channel width	l_g	15–25 mm	25 mm
Glottal channel minimum height	h_g	0–3 mm	0.2–1.5 mm
Glottal flow velocity	u_g	0–40 m s^{-1}	0–50 m s^{-1}
Oscillations fundamental frequency	f	80–250 Hz	0 Hz
Density	ρ	1.2 kg m^{-3}	1.2 kg m^{-3}
Dynamic viscosity	μ	1.8×10^{-5} Pa s^{-1}	1.8×10^{-5} Pa s^{-1}
Kinematic viscosity	ν	1.5×10^{-5} m^2 s^{-1}	1.5×10^{-5} m^2 s^{-1}
Reynolds number	Re	0–5000	0–5000
Modified Reynolds number	Re_δ	0–1000	0–800
Strouhal number	Sr	10^{-2}–10^{-1}	0

For each configuration, the experiments were repeated and reproduced. The experimental results presented in the following are averaged values for each considered parameter set $\{p_0, h_g\}$. Regarding the pressure at the minimum constriction height p_g, the measurements precision is globally within 10% for the uniform constriction, and within 15% for the round constriction. Regarding the flow-rate, the measurements precision is globally within 3% for both uniform and round constrictions.

2.2 Flow modelling assumptions

The dimensional analysis of flow conditions within the human glottis, as presented in Table 1, commonly leads to consider glottal flow as quasi-steady, incompressible, laminar flow.

2.3 One-dimensional flow model

The considered one-dimensional model relies on additional assumptions such as flow separation in the diverging downstream part of the glottal constriction and energy dissipation by turbulence downstream of the separation point x_s. Consequently the pressure at the separation point $p(x_s)$ is assumed to be equal to the downstream pressure (equivalent to the atmospheric pressure in this study). Bernoulli's principle is applied between the upstream of the constriction and the separation position. A viscous loss term (corresponding to the pressure drop in fully developed Poiseuille flow) is added. The pressure difference $p(x_0) - p(x_s)$ across the constriction drives the flow model which estimates from the streamwise height profile, $h(x)$ the glottal flow-rate, Φ and the streamwise pressure distribution, $p(x)$ such as

$$p(x) = p(x_0) - \frac{1}{2}\rho\frac{\Phi^2}{l_g^2}\left(\frac{1}{h^2(x)} - \frac{1}{h^2(x_0)}\right) - 12\mu\frac{\Phi}{l_g}\int_0^x \frac{\mathrm{d}x}{h^3(x)}. \tag{3}$$

This model is unable to predict the separation position which is determined from an ad-hoc separation coefficient c_s defined as $c_s = h_s/h_g$, where $h_s = h(x_s)$ and $h_g = h(x_g)$ denote the separation and minimum heights. A typical value $c_s = 1.2$ is commonly used in phonation models [20, 25]. In this study, the one-dimensional flow model is evaluated using this fixed value of c_s, as well as using values obtained from the two-dimensional model and from inverse estimation based on either pressure or flow-rate measurements [3].

2.4 Thwaites' method

Thwaites' method, which is associated to boundary-layer theory [21], allows one to keep a one-dimensional flow description, but can estimate the position of flow separation. In one-dimensional model, the continuity equation implies that $\Phi = l_g h(x)u(x)$. With the boundary-layer assumption, this expression becomes

$$\Phi = l_g(h(x) - 2H(x)\theta(x))u_e(x), \tag{4}$$

where $u_e(x)$ is the streamwise velocity profile in the main flow, $\theta(x)$ the profile of boundary-layer momentum thickness:

$$\theta^2(x) = \frac{0.45\nu}{u_e^6(x)}\int_0^x u_e^5(x)\mathrm{d}x, \tag{5}$$

and $H(\lambda)$ a shape factor depending on the parameter λ defined as

$$\lambda(x) = \frac{\theta^2(x)}{\nu}\frac{\mathrm{d}u_e(x)}{\mathrm{d}x}. \tag{6}$$

Thwaites' method relies on an iterative resolution of Eqs. 4–6 [28]. The separation position is determined from the parameter λ so that $\lambda(x_s) = -0.0992$ [18]. The assumptions regarding the flow properties downstream of the separation point are the same as those made for the one-dimensional model.

2.5 Two-dimensional laminar model

The two-dimensional laminar flow model considered in this study is based on the numerical resolution of the incompressible Navier–Stokes equation (Eq. 7) coupled to the continuity equation (Eq. 8), over a discretised two-dimensional flow domain:

$$\rho\left(\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u}\right) = -\nabla p + \mu\nabla^2\boldsymbol{u} \tag{7}$$

$$\nabla\cdot\boldsymbol{u} = 0 \tag{8}$$

This resolution is performed with the commercial software *ADINA* [1]. Even if only steady cases are simulated, the time-dependent terms are kept in the formulation of the equations to use artificial time-steps to gradually increase the inlet pressure value and to ensure the convergence to a solution. The dimensions and the boundary conditions applied to the fluid domains are described in Fig. 2. The problem is considered as symmetric to reduce the computational cost and to ensure the flow model stability. About 70,000 three-node finite elements are used to discretise the flow domain. For model stability and predictions accuracy purpose, the mesh density is higher within the constriction, as shown in Fig. 2. Preliminary tests showed that the obtained solutions are grid independent when the number of elements is over 50,000. These tests also showed that three-node elements are the most suitable to obtain the

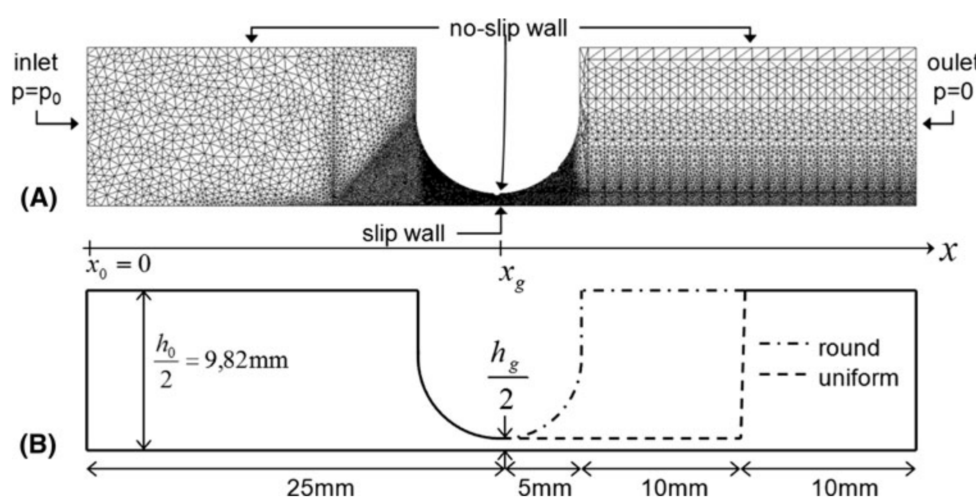

Fig. 2 **a** Mesh and boundary conditions of the two-dimensional fluid domain (round constriction). **b** Dimensions of the fluid domain for the uniform and round constrictions

convergence to a solution in all the considered cases. The iterative resolution of the problem, discretised with Galerkin method, is performed using a sparse solver and Newton–Raphson algorithm.

In this modelling, the flow separation position is computed from the wall shear stress distribution. Moreover, the two-dimensional velocity components (u, v) and the static pressure p are computed at every node of the mesh. So, contrary to the two previous models, flow properties are computed for the whole fluid domain.

3 Results

For the uniform and round constrictions, the models evaluation is based on the comparison between the computed and measured ratios between the upstream pressure p_0 and the pressure at the minimum constriction height p_g as function of modified Reynolds number Re_δ, which is proportional to the flow-rate Φ and the imposed minimum constriction height h_g, as defined in Eq. 2.

The comparison between the computed and measured data for the uniform constriction and four minimum apertures is shown in Fig. 3a. The comparison between the computed and measured data for the round constriction and four minimum apertures is shown in Fig. 3b. A logarithmic scale is used for the sake of the results clarity, especially for small Re_δ values.

The inverse estimates of the separation coefficient c_s obtained, by using the inverse one-dimensional model, from the pressure at the minimum constriction height p_g and from the flow-rate Φ are shown in Fig. 4. The values of c_s derived from the separation positions computed during the simulations carried out with Thwaites' method and the two-dimensional laminar model are also reported in Fig. 4. Smoke visualisation of the flow separation within the round vocal fold replicas are presented in Fig. 5 which illustrates qualitatively the evolution of the separation position as function of modified Reynolds number Re_δ.

An example of comparison between pressure, velocity and shear stress streamwise profiles computed with the different considered models are shown in Fig. 6. The case presented in that figure corresponds to the minimum constriction height $h_g = 0.5$ mm and the upstream pressure $p_0 = 500$ Pa.

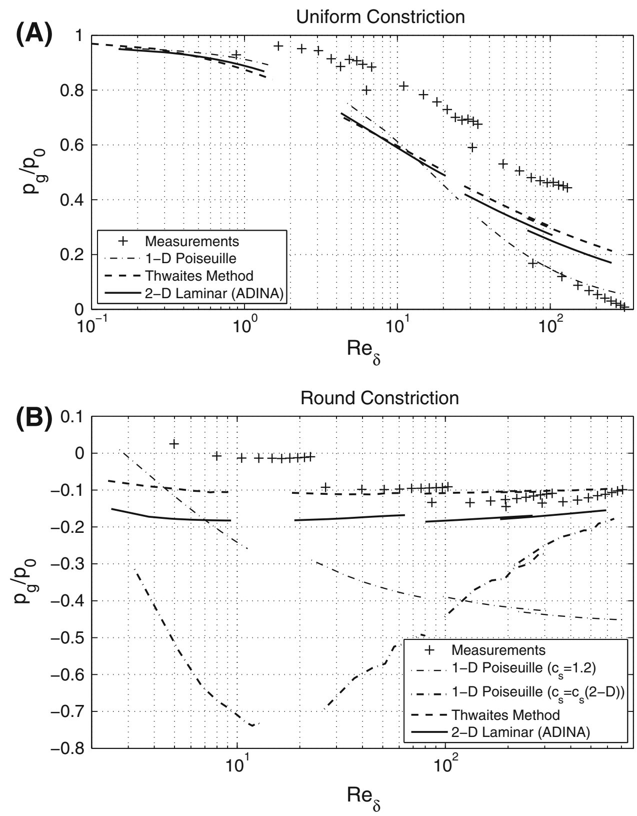

Fig. 3 Ratio between the upstream pressure p_0 and the pressure at the minimum constriction height p_g as function of the Reynolds number Re_δ, obtained experimentally and simulated with the three flow models, for the uniform constriction (**a**) and for the round constriction (**b**) with four apertures

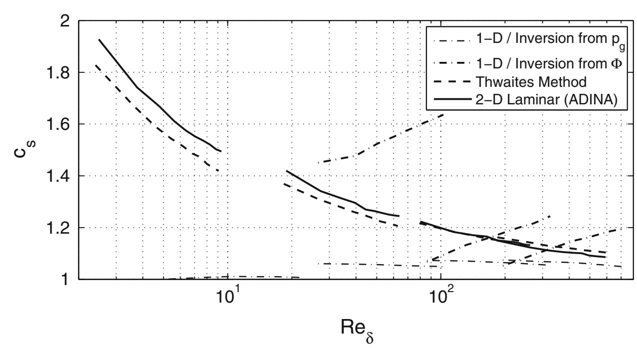

Fig. 4 Separation coefficient c_s as function of the Reynolds number Re_δ, obtained by inversion with one-dimensional model and simulated with the two other flow models, for the round constriction with four apertures

4 Discussion

4.1 Uniform constriction

The three considered flow models predict a decrease of the pressure ratio p_g/p_0 as Reynolds number Re_δ increases. This evolution is qualitatively in agreement with what is obtained experimentally. Nevertheless, it can be seen from Fig. 3a that for each model, the simulated data describe a smooth curve, particularly in the transitions between two cases corresponding to different minimum apertures h_g. On the contrary, these transitions appear more distinctly for the

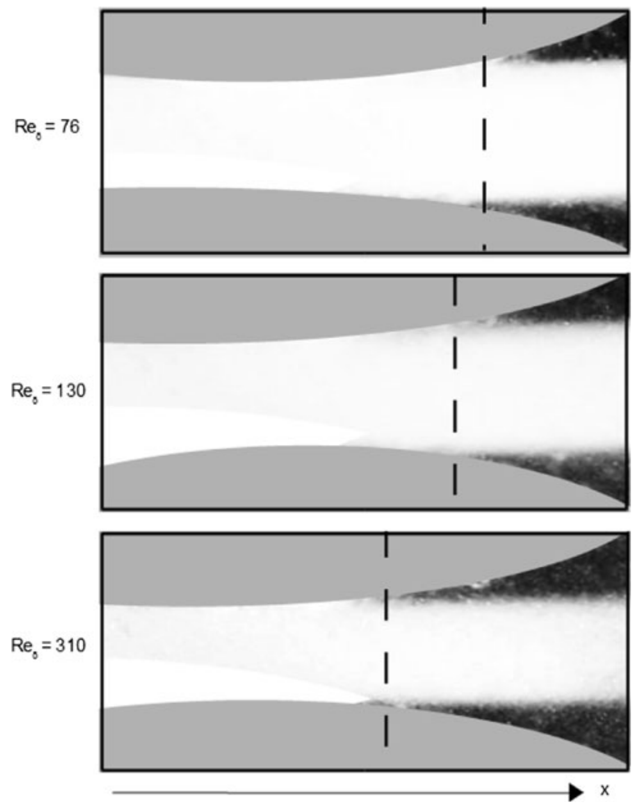

Fig. 5 Smoke visualisation of the flow separation within the round vocal fold replicas with the minimum constriction height $h_g = 1.0$ mm. The separation positions (estimated on the visualisation) corresponding to three modified Reynolds number Re_δ are indicated with *dashed lines*

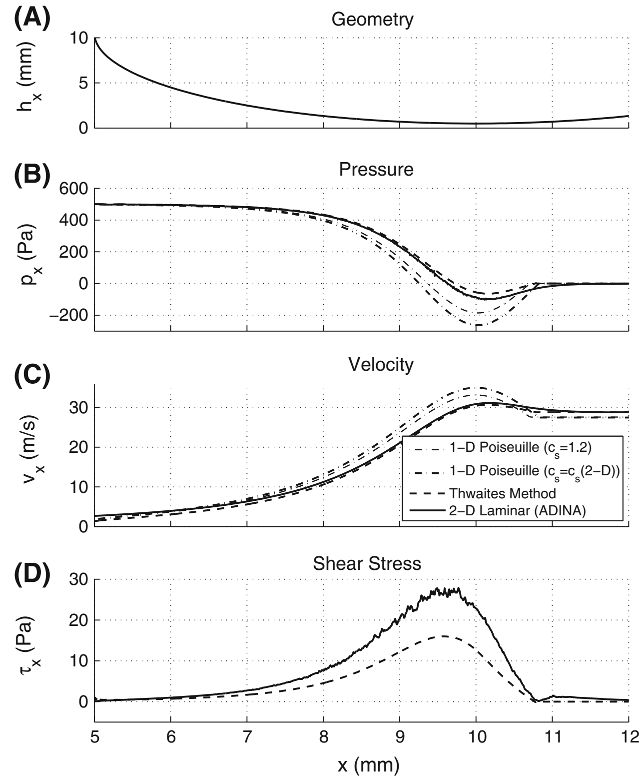

Fig. 6 Simulated streamwise profiles for the round constriction with the minimum constriction height $h_g = 0.5$ mm and the upstream pressure $p_0 = 500$ Pa: **a** geometry, **b** pressure, **c** velocity and **d** shear stress as function of the x-coordinate

measured data, with a difference of 0.1 between the pressure ratios corresponding to $h_g = 0.2$ and 0.5 mm ($Re_\delta \approx 6$) and between the pressure ratios corresponding to $h_g = 0.5$ and 1.0 mm ($Re_\delta \approx 30$), and a difference of 0.3 between the pressure ratios corresponding to $h_g = 1.0$ and 1.5 mm ($Re_\delta \approx 75$). Indeed, aperture $h_g = 1.5$ mm corresponds to the upper portion of the considered Re_δ range ($Re_\delta > 100$) where the effects of viscosity are very small compared to flow inertia. For this aperture and this Re_δ value, the flow through the in-vitro replica and the resulting jet are likely to be turbulent whereas it remains laminar for the three other apertures. Indeed, it can be seen that the three laminar models predict p_g/p_0 ratios inferior to the measured ones for $h_g = 0.2$, 0.5 and 1.0 mm whereas they predict superior ratios for $h_g = 1.5$ mm. For the three smaller apertures, the three models underestimate the effects of viscosity on the pressure within the constriction and overestimate them for $h_g = 1.5$ mm.

The models comparison shows that the flow quantities estimated by Thwaites' method, and the two-dimensional laminar model are very similar for all imposed conditions since the pressure and flow-rate predictions of these two models are within 5%. For $Re_\delta \leq 20$, it can be seen from Fig. 3a that the one-dimensional model predicts pressure ratios p_g/p_0 comparable to those predicted by the two other models ($|p_g^{1-D} - p_g^{ADINA}|/p_0 < 0.05$). For $Re_\delta > 20$, the viscosity related corrective term in Eq. 3 becomes negligible compared to Bernoulli's term. Therefore the p_g/p_0 ratio computed by the one-dimensional model tends more rapidly to 0 when Re_δ increases, so that $0.1 < |p_g^{1-D} - p_g^{ADINA}|/p_0 < 0.15$. Consequently, the one-dimensional model pressure predictions are closer to the measured data than the two other models predictions for $h_g = 1.5$ mm ($|p_g^{1-D} - p_g^{measured}|/p_0 < 0.03$ and $|p_g^{ADINA} - p_g^{measured}|/p_0 < 0.2$).

Regarding the flow-rate, all the considered models systematically underestimate the measured values, especially Thwaites' method and the two-dimensional laminar model. The one-dimensional model appears to be the best estimator of the measured flow-rate ($2\% < |\Phi^{1-D} - \Phi^{measured}|/\Phi^{measured} \leq |\Phi^{ADINA} - \Phi^{measured}|/\Phi^{measured} < 80\%$). The differences between the models flow-rate predictions confirm that flow-rate estimations provided by a two-dimensional laminar model are always inferior to those obtained by one-dimensional models [7].

4.2 Round constriction and flow separation

As observed for the uniform constriction, the underestimation of the measured flow-rate by the models also appears for the round constriction.

Regarding the pressure within the constriction, the predictions obtained with Thwaites' method and the two-dimensional laminar model are qualitatively in agreement with the measurements. For $Re_\delta > 30$, both models provide accurate estimates of the pressure p_g at the minimum constriction height ($|p_g^{\text{Thwaites}} - p_g^{\text{measured}}|/p_0 < 0.04$). For $h_g = 0.2\,\text{mm}$, the experimental control of the imposed aperture becomes more difficult so that standard deviation on pressure measurements is higher than for the other apertures. For a diverging constriction, the one-dimensional model pressure predictions are strongly dependent on the choice of the ad-hoc separation coefficient $c_s = h_s/h_g$ [3]. The use of a constant value as geometrical criterion for the determination of flow separation leads to pressure predictions irrelevant to the in-vitro measurements, as shown in Fig. 3b.

The inversion approach applied to one-dimensional flow models [3] allows the estimation of the separation coefficient needed to predict the measured values of either the pressure p_g at the minimum constriction height or the flow-rate Φ. The separation coefficients estimated from p_g are situated between 1 and 1.1. However, the evolution of c_s as function of Re_δ is not physical since the value of c_s increases, as the minimum aperture h_g increases. The separation coefficients estimated from Φ are different from those estimated from p_g. However, the value of c_s increases, as the flow-rate Φ increases. This evolution of c_s as function of Re_δ is the opposite of that observed experimentally and qualitatively illustrated in Fig. 5 so that it is not physical either.

Thwaites' method and the two-dimensional laminar model are able to predict the flow separation position. Separation coefficients can be extracted from the computed separation positions to establish a link with the one-dimensional ad-hoc criterion, as shown in Fig. 4. The two models predict a physical evolution of the separation coefficient since c_s decreases when Re_δ increases. Moreover, the c_s values predicted are very similar even if the discrepancy between the two models predictions increases when Re_δ decreases. Figure 4 shows that determining flow separation from only geometrical criteria is not relevant if the whole range of flow conditions corresponding to glottal flow is considered. Therefore, it could be interesting to use the separation coefficient predicted by two-dimensional laminar model to improve the predictions of one-dimensional model. Such approach was used to determine the parameters of a simplified vocal fold model from finite-element simulations [5]. However, the computed separation coefficients are very different from the values obtained by inversion. Then, it can be seen in Fig. 3b that the one-dimensional model using the c_s values extracted from simulations with the two-dimensional laminar model still overestimates the pressure drop within the constriction and provides irrelevant predictions.

Thwaites' method and the two-dimensional laminar model predict very similar separation positions, but a quasi-constant discrepancy ($|p_g^{\text{Thwaites}} - p_g^{\text{ADINA}}|/p_0 \approx 0.07$) appears between the pressure predictions provided by these two flow models, as shown in Fig. 3b. This discrepancy can be explained by the assumption regarding the pressure downstream of the separation point made in Thwaites' method. The pressure profiles presented in Fig. 6b show that the pressure at the separation point is, by assumption, equal to the downstream pressure in the Thwaites' method profile whereas the pressure at the separation point computed by the two-dimensional laminar model is inferior to the downstream pressure. The strict condition used in Thwaites' method leads to a difference in the determination of the pressure within the constriction. Figure 6b also illustrates the overestimation of the pressure drop within the round constriction obtained with the one-dimensional model. Regarding the velocity, the difference between the models predictions is relatively less notable. The velocity profiles presented in Fig. 6c show in particular that the velocity values computed by all the considered models at the exit of the constriction are very similar. Finally, one particular benefit of using more advanced glottal flow models is the estimation of the wall shear stress exerted by the flow. The comparison between the computed stress profiles presented in Fig. 6d shows that the stress estimated from Thwaites' method is almost half the one estimated from two-dimensional laminar model. The use of more sophisticated flow models gives a more detailed description of the glottal flow behaviour. Consequently, the flow models evolution should be accompanied by the evolution of the experimental set-ups and replicas to validate the relevance of the computed properties. Experimental data referring to the separation position and the jet formation would allow the evaluation of the relevance of the assumptions on these phenomena made for glottal flow modelling.

In conclusion, this study shows that all the considered models underestimate the flow-rate with respect to the measurements and that the simplest model gives the more relevant flow-rate estimations. However, one-dimensional flow modelling can only provide qualitative predictions of the pressure profile within the glottal constriction, whereas Thwaites' method and the two-dimensional laminar model give estimations of the pressure drop in better agreement with the measurements. The assumptions on the flow properties in the separation region can have an important impact on the pressure predictions. This motivates further investigations using flow models which take into account turbulence and three-dimensional effects.

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