Experimental and numerical study of patterns in laryngeal flow

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Abstract. Unsteady airflow is investigated in a channel with a geometry approximating that of the human larynx. The laryngeal flow is simulated by solving the Navier-Stokes equations for an incompressible two-dimensional viscous fluid, and visualized using the Schlieren technique in an experimental setup consisting of a rigid replica of the larynx, with and without ventricular bands. This study shows the spontaneous formation of vortex couples in several regions of the laryngeal profile, and at different stages of the evolution of the starting glottal jet.

1. Introduction

The interest in unsteady flow through the larynx has been renewed with the evidence that certain unsteady effects may be relevant to model the phonation process correctly [1, 2]. The dynamics of an unsteady flow through a channel with constrictions is a very general problem in fluid mechanics. The human larynx forms an airway with two consecutive constrictions. The first constriction is defined by the vocal folds, which are a pair of mucous membranes stretched horizontally across the larynx (see Fig. 1). The second constriction is determined by the so called false vocal folds or ventricular bands, which are a pair of thick mucous structures located slightly above the true folds. During voice production, pressure from the lungs supplies the energy for sustaining vocal fold oscillations. The false vocal folds are poor vibrators, due to their more viscous and less stiff properties which prevent their vibration in normal speech. Independently of whether they vibrate or not, the literature indicates the tendency of the false vocal folds to adduct toward the midline during phonation. Once adducted, both true and false vocal folds, define a region between them called the laryngeal ventricle (or Morgagni’s ventricle).

In 1955, Lee studied a steady laminar flow through a double constriction, varying the size of the second constriction, the proximity of the two constrictions and the flow rate. He found that the farther the two constrictions were from each other, the less complex was the effect on the flow near the first constriction. It is therefore reasonable to speculate that the presence of the laryngeal ventricle is not innocuous when it comes to characterizing the flow through the glottis. It is an open question whether airflow complexity certainly affects vocal output by modifying glottal flow, altering airflow resistance and affecting the source acoustics. In any case, as indicated by both van den Berg and Lee [3, 4], the effects of supraglottal structures on the flow will ultimately depend on their shape and size.
In order to investigate the influence of the geometry on laryngeal flow, the authors have considered the aerodynamic impact of the ventricular bands of both in vitro and in silico (numerical) experiments [5]. These experiments are performed in a static but adjustable geometry, in which the false vocal folds can be either removed or inserted at different locations in the laryngeal channel. The first constriction is modeled as a slitted nozzle in a duct. Previous experiments have shown that the essentially planar jet that exits the vocal folds has the shape of a sliced mushroom-like current [1]. This mushroom structure corresponds in fact to a dipolar vortex front, i.e. to a couple of closely packed counter-rotating circulations. Indeed, plane jets and vortex dipoles are supposed to be united by the same mechanism of generation: the action of a localized source of momentum in a viscous fluid [6].

In this work, we present experimental and numerical evidence that these flow patterns are characteristic of the first stages in the evolution of the starting jet that traverses the double constriction defined by the folds in the larynx. A qualitative description of the relevant phenomena involving this type of structures in a schematic laryngeal geometry for an impulsively starting jet is provided.

2. Methods
2.1. Experimental setup
Our experimental setup to analyze an impulsively starting flow can be divided into three main parts. One of them is the Schlieren system, an optical system that allows us to observe index of refraction gradients in a transparent fluid [7]. Changes of fluid density are the usual source of variations in the refraction index. The second part of the setup consists of a pneumatic circuit that feeds a replica of the larynx, the third part of the setup. The laryngeal replica is composed of a metallic base including rigid 25mm-thick vocal folds, with a rounded geometry. This base is coupled to a supraglottal structure completely designed in acrylic glass (PMMA) with unmountable false vocal folds, also having a rounded shape (radius of curvature of 5mm). The parameters that can be varied in this geometry are the distance $h_{vf}$ between the vocal folds (1 or 2mm), the separation $h_{vb}$ between the ventricular bands (2, 4 or 6mm) and the distance $L_v$ between the vocal folds and the ventricular bands (10, 20 or 30mm) that define the laryngeal ventricle.

The Schlieren system (Fig. 2) built in our laboratory is a typical symmetrical Z-type system with two 0.5m diameter spherical mirrors with focal lengths of 3.0m. A rapid CMOS camera served as acquisition device for the Schlieren images, allowing recording frequencies of 50, 100 or
Figure 2. Diagram of the Z-type Schlieren system. Mirrors are spherical with a diameter of approximately 0.5m and a focal distance of 3m.

Figure 3. Diagram of the pneumatic circuit.

200 frames per second. When the frequency doubles, the spatial resolution of the image halves in the vertical direction. Both the illumination source and the knife-edges are placed at the mirror’s focal distance. A pair of mutually perpendicular knife-edges placed in the focus of the second mirror help to improve the contrast in the Schlieren images.

Helium gas is introduced in the flow as a tracer through a lateral orifice immediately upstream the folds. A Helium compressed tank is used to feed the system with this gas. A pressure regulation device connected to the tank enables to control the mass flowrate of this gas, which tends to result quite reduced compared to the air mass flowing between the folds. Because the device is operated with a small amount of tracer introduced in the flow, the system enables a very good contrast during the transients.

The air pneumatic circuit (Fig. 3) consists mainly of a 400dm³ recipient fed by a compressed air tank. The amplified signal from a calibrated differential pressure sensor is transmitted to a computer, which monitors the pressure build-up inside the recipient when it is filled with dry air. Once the desired pressure is attained, the tank is isolated from the circuit by means of a two way valve. A system of hoses connects the recipient in series with a solenoid two way valve, a flow-meter and finally to the lower extreme of an 80cm length and a 2.5cm (inner) diameter aluminium tube. The response time of the solenoid valve (normally closed) at the opening is approximately 5ms.

The larynx replica is mounted on the tube’s superior extreme, where pressure equals the
Figure 4. Laryngeal channel geometry and boundary conditions for the direct numerical simulations. The incoming velocity is set to increase following an initial linear ramp of 5 m/s.

atmospheric pressure. Thus, when the solenoid valve is energised, the air flows along the ducts from the recipient to the replica, passing through the vocal folds. The flow rate, which is conserved along the circuit, is measured in steady regime by the flow-meter. This value is chosen to be representative of a suitable airflow velocity between the vocal folds in accordance with typical values for the human larynx (15 m/s).

2.2. Numerical technique
In order to simulate the airflow through a schematic larynx corresponding to the experimental setup, we use a numerical code which has been specifically conceived to simulate unsteady airflow through a two-dimensional glottal model [2]. It uses a multigrid finite-difference method and a fixed Cartesian grid that guarantees that the discretization scheme is not degraded by non orthogonal frames. The equations are integrated with a time marching algorithm based on a prediction projection method. The spatial discretization uses a staggered grid. The immersed boundaries are taken into account through a phase function set to 0 or 1 for fluid or structure cells respectively.

Solutions are computed in a rectangle of unit height and adjustable length, shown in Fig. 4. The design of the flow boundaries corresponds to the geometry of the channel and replica used in the experimental setup. The rectangle has $N_x \times N_z$ rectangular cells. The Reynolds number is built on the channel's maximum height and the incoming velocity. The computations in this work are performed on grids with $N_x = 512$ or 1024 and $N_z = 128$ or 256. The dimensionless time step used in the calculation is of order $10^{-4}$ to $10^{-5}$. For the lower spatial resolution, the coarse mesh is refined around the axis and next to the boundaries.

Boundary conditions are also set in accordance with the experiment. The value of the incoming velocity can be set either constant or time-dependent. We have performed numerical simulations with an initial linear ramp in order to match the response time of the solenoid valve. After this transient, the value of the flow rate is kept constant in time, both in numerical and physical experiments. The maximum value of the flow rate is established in correspondence with the value measured with the flow-meter of the experimental setup at very large times, a value which is used to choose the Reynolds number for the numerical experience. Velocities are set to zero in the structure cells. The inlet flow enters a channel where the fluid is initially still. On the solid walls we impose the classical no-slip and no-injection condition. At the
downstream boundary, we impose the so-called advective-type boundary condition, the most natural boundary condition for a transparent artificial boundary. This condition reduces to a homogeneous Neuman condition if the flow reaches a steady state. No symmetry condition is forced along the axis, to capture possible flow asymmetries.

3. Results
Photographs of the different stages in the evolution of the starting jet in laboratory and numerical experiments are shown in Fig.5-9. At the exit of both constrictions, laboratory results clearly show the spontaneous formation of flow patterns which can be associated to a jet with a vortex dipole at its head. Smaller dipoles seem to form spontaneously within the ventricular cavity defined by the false vocal folds.

Numerical simulations show, during the jet formation stage, a starting jet that emerges from the vocal folds with a front composed by symmetrical opposite-sign vortices forming the mushroom-like cap which is typical of a pulsed injection of fluid (Fig. 5). This mushroom structure is easy to identify in the Schlieren images. The head of the jet progresses along the duct with a convection speed which amounts to about $9 \text{m/s}$ for $Re = 900$ and a $1 \text{mm}$ aperture for the vocal folds. This value is not significantly altered by the presence of the ventricular bands (Fig. 6). Along the boundary layers of opposite vorticity that delimit the evolving jet, it is possible to observe, after a certain time, the subsequent formation of the series of smaller dipolar structures, which bear a strong resemblance with the structures observed in certain oceanographic situations [8].

When the ventricular bands are present, a second jet is born at the exit of the constriction that they define (Fig. 7). This second jet is born simultaneously with the first jet if both structures (folds and bands) are equally constricted. If the aperture at the bands is wider than the glottal aperture, there is a delay in the birth of the second jet which is proportional to the ratio between the band and fold apertures. The jet emerges from the ventricular bands at a speed which depends on the ventricular aperture: the less constricted the bands are, the slower the final jet progresses. The size of the jet past the ventricular bands (which is also determinant of the size of the dipolar head of the final supralaryngeal jet) is also proportional to the ventricular aperture.

The flow patterns observed in the ventricle after the instant in which the first jet (the glottal jet) impinges on the ventricular bands are quite complex in all the tested geometrical configurations. Numerical simulations show that small-sized vortex dipoles are shed symmetrically in the upstream side of the walls of both ventricular bands. These small patterns initiate a sinuous trajectory firstly away from the jet and then back towards the jet axis,
Figure 6. Jets emerging from the vocal folds at the initial stages of the flow onset with $Re = 900$ with ventricular bands ($L = 25\text{mm}$, $h_{vb} = 6\text{mm}$). Above: Schlieren image, below: vorticity in numerical simulation.

Figure 7. Jet emerging from the ventricular bands with $Re = 900$ for a glottal opening of $2\text{mm}$ and a band opening of $4\text{mm}$. $h_{vb}/h_{vf} = 2$. Above: Schlieren image, below: vorticity in numerical Simulation.

Figure 8. Persistent structure of symmetrical vortices of opposite sign within the ventricle for $Re = 900$ in two different geometrical configurations. Left: Schlieren image, right: vorticity in numerical simulation.

contributing to form, after the initial phase, two relatively large vortices of opposite sign in either side of the jet within the ventricle (Fig. 8) which tend to persist in all the numerical experiments performed with ventricular bands. These large vortices are also visible and persistent in the Schlieren visualizations. The time needed for these vortical structures to settle depends on $U(t)$ and $h_{vb}$.

At larger times, a three dimensional flow pattern is observed for the laboratory flow past the ventricular bands (Fig. 9). At some distance from the ventricular bands a slug flow type is established that occupies the whole section. At the exit of the ventricular aperture, the jet is still visible, surrounded by vortical structures which are similar to the ones observed within the ventricle in the previous stage of the flow. The two-dimensional numerical experiments do
Figure 9. Loss of stability of the supralaryngeal jet Above: through vocal folds, below: through ventricular bands.

not reproduce this 3D instability. They are not meant to correctly estimate the transition to turbulence, but to study the flow patterns that prevail in the initial stages, which they predict correctly.

4. Conclusions
In the present study, we have performed numerical and laboratory experiments on the basis of two-dimensional and rigid models of the larynx, with and without false vocal folds.

Summarizing the results presented above, the dynamics of an impulsively starting flow through a double constriction is characterized by a double jet (one per constriction). The jets exiting the slitted constrictions have a head which is structured as a vortex dipole. These dipoles are known to have a fast translating motion and a relatively long lifetime, unless they interact with other structures or collide against a wall. This is exactly what happens when the ventricular bands or false vocal folds are present. As a result, the complexity of the flow is clearly affected by the presence of the laryngeal ventricle, in which resident vortical patterns seem to settle after a collective interaction of a sequence of small scale dipoles shed by the upstream side of the ventricular bands.

The next natural step in our study is to quantify the properties of the observed patterns and, if possible, to give a theoretical model of the dynamics of these structures that helps unveiling their possible role in the larynx.

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