Vortex Identification in the Human Epiglottal Region From POD-Reconstructed Velocity Fields

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Abstract PIV measurements have been made at four locations in the ETA model (from pharynx to trachea) at a flow rate corresponding to 10 l/min in the prototype. The corresponding Reynolds number $Re$ based on the inlet condition is 716. Two thousand images were acquired at each location at a framing rate of 2 Hz. The mean velocity and turbulence quantities were then calculated. In addition, the POD method was applied to the data in the pharynx region to expose vortical structures. Only four modes were used for POD reconstruction which recovered about 60% of the turbulent kinetic energy. Then a vortex identification algorithm was employed to identify and measure properties of the exposed structures. This step was followed by a statistical analysis of the distribution of size and strength of these vortices.

The results showed that the flow is characterised by regions of a jet-like flow and re-circulating flows. In addition, the mean turbulence quantities and POD-reconstructed fields highlighted some interesting features that occur in the pharynx region near the epiglottis. This statistical analysis showed increased strength of the counter-clockwise structures in that region compared to clockwise structures.

1. Introduction

Aerosol drug delivery to the lungs using “puffers” is strongly dependent upon knowledge of the complex flow field generated in the human extra-thoracic airway (ETA) during the inhalation phase. That is, the human mouth, including teeth and tongue, provide significant geometrical obstacles to delivery of drug distal to the targeted location. Previous studies have found that 80–95% of an orally inhaled dose is deposited in the ETA and channelled to the gastrointestinal tract (see Johnstone et al., 2004), which causes unwanted systemic effects. In order to maximize delivery to the targeted lung tissue, it is important to understand the human ETA flow field that could drive the creation of alternate delivery mechanism to achieve minimal drug deposition in the ETA.

The complexity of the extra-thoracic airway (ETA) flow field also poses serious challenges for experimental measurement, and relatively few such measurements are available in the literature. Heenan et al. (2003) and Johnstone et al. (2004) studied experimentally the flow in an idealized human ETA using endoscopic particle image velocimetry (EPIV) and hot-wire anemometry (HWA) techniques, respectively. These experimental studies were planned to provide validation and confirmation for more detailed computer simulations. However, Ball et al. (2008a), who studied computationally the flow field in the ETA using the lattice-Boltzmann method (LBM), demonstrated that EPIV (Heenan et al., 2003) and HWA (Johnstone et al., 2004) measurements were not completely reliable when compared to results from a variety of turbulence models. Specifically, hot-wire measurements were not reliable in zones with recirculation and secondary flows, whereas EPIV measurements were influenced by optical access and seeding limitations. A
complete discussion of the above problems is presented in the recent review by Kleinstreuer & Zhang (2010).

In an effort to understand the dependence of airflow on the geometry, Lin et al. (2007) investigated computationally the flow field in a realistic upper respiratory tract. The geometry included a mouthpiece, the mouth, the oropharynx, the larynx, and the intra-thoracic airways of up to six generations. The POD analysis of the flow revealed that the regions of high turbulence intensity were associated with a pair of counter-rotating vortex elements which extend from the laryngopharynx to the glottis, which corroborates the computational results of Ball et al. (2008b) who used idealised geometry. These structures resemble “pulsating Taylor-Görtler-like” vortices. They also found that the locations of these vortices coincide with the local maximum turbulent kinetic energy.

The three-dimensionality, turbulence, and high spatial gradients of the ETA flow field make a comprehensive survey using pointwise-measurement techniques such as laser-Doppler velocimetry (LDV) impractical, requiring thousands of individual measurements to resolve the time-averaged flow. Particle image velocimetry (PIV) is a clear choice for this kind of study. Consequently, the practical approach is to build a transparent model with an index-matched working fluid and use standard PIV imaging and laser delivery systems. The main motivation behind this work is to provide insight into the structure of human ETA flow. This work is concerned with only the fluid mechanics of the inspired flow and does not attempt to consider the effect of these flow patterns on aerosol transport. Specifically, the objective of this study is to carry out an experimental investigation of the flow field in an idealized human ETA model using a PIV system. This was achieved by investigating the mean velocity and turbulence parameter fields. In addition, the instantaneous velocity fields were analysed by the POD to expose the energetic vortical structures in the flow. This step was followed by quantifying properties of the vortical structures using a vortex identification algorithm, and performing a statistical analysis of the distribution of the structures.

2. The idealized geometry and model construction

The geometry of the extra-thoracic airway (ETA) is complex and varies largely from person to person. It even varies with inhalation rates and disease states. For these reasons, it is found that creating an idealised model that represents averaged-extra-thoracic airways geometry of healthy individuals is more practical. This enables direct comparison between different experimental and computational data obtained in the same geometry, and is also suitable for CFD studies because extremely high grid resolutions are not needed at the walls to resolve all of the small airway irregularities as in realistic models. Figure 1 displays a sagittal view of the idealised ETA model. The idealised geometry possesses all the basic anatomical features of real ETA geometry. The main components of the ETA model include the oral cavity (mouth), the pharynx, the larynx, and part of the trachea. Note that the nasal cavity is not included in the model because it is assumed to be blocked off during oral inhalation. This design was developed based on information from magnetic resonance imaging (MRI) and computed tomography (CT) scans, direct observation of living subjects, and data in the archival literature. The rationale behind the geometry and choice of dimensions are fully described in Stapleton et al. (2000).

The transparent flow passage needed for the PIV measurements was produced largely using the process described by Hopkins et al. (2000) which is summarized here. The flow passage was made by pouring a silicone-based material (Sylgard 184 silicone elastomer) around a rapid-protoype wax cast of the idealized ETA placed in a Plexiglas box. The wax cast was then flushed out with hot water, leaving an ETA replica within the clear silicone through which flows an index-matched aqueous glycerol. It was decided to use a double scale model to improve the accuracy of the
measurements. This scale was also adopted by Heenan et al. (2003) and Johnstone et al. (2004) in their studies for similar reasons.

![Diagram of ETA model](image)

Figure 1: Geometry of the idealized ETA model which shows all basic anatomical features of the human ETA.

### 3. Experimental apparatus

The ETA model was installed in a closed re-circulating flow system as shown in Figure 2. The experimental setup consists of a pulseless impeller pump, a feeding reservoir, and a flow conditioner. The pump provided a steady flow and was regulated by a DC controller. After exiting the model, the working liquid (aqueous glycerol) returns to the feeding reservoir. A bypass, contains a 1 $\mu$m filter, was used to filter the working liquid before seeding with fluorescent particles for PIV measurements.

The flow was conditioned at the inlet to the ETA model using a settling chamber and nozzle (see Figure 2). It was attached directly to the inlet of the model and consists of a 152.4 mm long, 114.3 mm diameter section, which contains two screens and flow straightening vanes. The straighteners were made up of plastic straws with a length to diameter ratio ($l/d$) of 20; while the screens (mesh number 15) were placed immediately upstream and downstream of the straighteners (see Figure 3). After the flow conditioner, the cross-sectional flow diameter reduces at the exit of the flow conditioner (the entrance to the model) by a circular arc exit with a radius equal to the exit diameter (38.1 mm). The coordinate system used in this paper has its origin on the centre of the flow-conditioner exit nozzle with positive $x$ to the right and $y$ downward as shown in Figure 1.

In order to avoid optical distortion of the light scattered from the fluorescent particles in the flow passage, the refractive index of the working fluid was matched with the model material by using a glycerol/water mixture. A grid of lines was placed behind the model and a mixture with excess glycerol was pumped through the model. Water was then added to the mixture (at small increments) until the distortion in the gridlines disappeared. The ratio of water to glycerol was approximately 59% to 61%, respectively. The refractive index was then measured using ATAGO PAL-R1 refractometer and was 1.41. The experiments were carried out at a constant temperature of 25.5 °C.
by using an auxiliary water loop which consisted of a heater, a temperature controller, and a thermocouple placed at the inlet to the flow conditioner (see Figure 2). The dynamic viscosity and density of the mixture were measured and determined to be 8.23 cp and 1130.37 kg/m$^3$, respectively. Since the ETA model is scaled to a factor of 2 and the working fluid is different than air, the relationship between the model and the actual human ETA (the prototype) was established based on the Reynolds number $Re$. Thus, the flow rate reported in this paper ($Q = 10$ l/min) is with respect to flow in the actual human ETA.

4. PIV analysis

The PIV system used 120 mJ/pulse dual Nd:YAG lasers of 532 nm wavelength generated from a New Wave Research Solo PIV laser system. The light sheet was formed through a 250 mm focal length spherical lens and a –25 mm focal length cylindrical lens. The resulting light sheet was
approximately 1 mm thick in the area of interest. The light sheet was oriented vertically and included the sagittal (central) plane of the model. After carefully filtering the water through a 1 μm filter, silicon carbide seed particles were introduced. These particles have a specific gravity of 3.2 and a mean diameter of 2 μm yielding a Stokes settling velocity of 0.00055 mm/s. Therefore, these particles are expected to faithfully follow the flow.

The field-of-view was imaged with a 2048×2048 pixel FlowSense camera operating in dual capture mode. The camera was fitted with a 60 mm Micro-Nikkor lens and the object distance was adjusted to give the field-of-view (FOV) required for each image. Image calibration was achieved by taking a picture of a steel ruler with 1 mm divisions. Two thousand image pairs were acquired at each location at a framing rate of 2 Hz.

Image analysis was performed with correlation analysis DynamicStudio v2.3 software developed by Dantec Dynamics. The images were analysed with 64 × 64 interrogation areas using the adaptive correlation between successive images. The interrogation areas were overlapped by 50%. The correlation peak was located within sub-pixel accuracy using a Gaussian curve-fitting method. This analysis process yielded a final interrogation area size of 32 × 32 pixels. Table 1 summarizes the size and resulting spatial resolution of the velocity fields reported in this paper. Note that the horizontal and vertical locations (see Table 1) represent the distance from the origin to the top left corner of the field-of-view. After the correlation analysis was complete, outliers were rejected using the cellular neural network (CNN) method (Liang et al. 2003) with the variable threshold technique of Shinneeb et al. (2004). The main idea of this technique is to use information about the local velocity gradient in the flow to make a local choice for the threshold. The percentage of vectors rejected was ~4%. Rejected vectors were replaced using a Gaussian-weighted mean of their neighbours.

<table>
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<th>Vertical location (mm)</th>
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5. Eduction of vortical structures

The key attribute of coherent structures is that they are vortical, i.e. they have large vorticity concentrations in two or three dimensions. To consider them as vortices has been well accepted and the term vortex has often been used for coherent structures like vortex rings or vortex pairs (Hussain, 1986). The definition of a vortex has been extensively discussed and a number of different definitions have been offered (Robinson, 1991; Jeong & Hussain, 1995). However, the calculation of vortex statistics (i.e. diameter, strength, etc.) is normally accomplished by identifying isolated regions of significant vorticity known as vortex cores (Adrian et al., 2000).

The technique used in this paper to expose coherent structures is the proper orthogonal decomposition (POD). POD provides an efficient way to extract the most-energetic components of
an infinite-dimensional process and is applicable to inhomogeneous turbulent flow fields (Adrian et al., 2000). The procedures adopted in this paper may be summarised as follows. The PIV velocity fields were time-averaged and the fluctuations calculated. The method of snapshots (Sirovich, 1987) was applied to the data. The velocity fields from which vortices were identified were reconstructed using only a few POD modes. The reconstructed fields were then processed using the vortex identification algorithm described in Agrawal & Prasad (2002). Briefly, this technique involves searching the POD-reconstructed field for circular streamlines by monitoring the change in direction of the measured velocity vectors along expanding circular paths surrounding candidate vortex centres. The largest such path for which the change in direction is monotonic for 75% of the vectors defines the size of the vortex. This threshold (75%) was selected after investigating several thresholds in the range 65% to 90%, which showed that the mean vortex size $R_m$ and circulation $\Gamma_m$ becomes independent of the thresholds in the range 75 – 80%. The preference was for a 75% threshold after visual inspection of individual vortices (see Shinneeb, 2006 for more details).

The circulation $\Gamma$ of a structure was calculated by integrating along a polygon path as follows:

$$
\Gamma = \sum (u_{\text{POD}} \Delta x + v_{\text{POD}} \Delta y)
$$

where $u_{\text{POD}}$ and $v_{\text{POD}}$ represent the velocity components of the POD-reconstructed field, and $\Delta x$ and $\Delta y$ are the horizontal and vertical spatial intervals, respectively. Due to the discrete nature of the data, the path was approximated by the polygon that best describes a circle.

6. Results

This section presents results of the PIV measurements in the ETA which included the flow field from the pharynx region to the trachea (see Figure 1). The flow rate was 10 l/min. The corresponding Reynolds number based on inlet condition is 716. The mean flow and vortical structures results are presented below.

6.1 Mean velocity field

The mean velocity was calculated from 2000 instantaneous velocity fields that were acquired at each location at a sampling rate of 2 Hz. Figure 4 shows four vector plots of the mean velocity fields. The size and spatial resolution of the fields-of-view are given in Table 1. Both $x$ and $y$ are normalized by the exit nozzle diameter $D$ of the flow conditioner. Note that the vertical distance $y$ is positive downward. Also note that not all vectors are shown in the plots to avoid cluttering on the figures.

Figure 4(a) shows an interesting behaviour of the velocity field captured in FOV1 (see Figure 1). It shows that the gradual reduction to a very small cross-sectional area at the back of the oral cavity ($y/D \approx 2.4$), whose cross-sectional area is the smallest in the pharynx region, has the effect of resetting the flow and producing a relatively high mean velocity flow. The velocity profile here is very nearly top-hat shaped. At downstream locations, the sudden expansion of the cross-sectional area distal to the pharynx led to a formation of a large-recirculation flow as shown in Figure 4(b) (right side of the FOV2). At downstream locations, the cross-section of the flow decreases again by the existence of the epiglottis (represented by a gray shape in Figure 4b and 4c). Note that the missing velocity profiles in the range $3.64 < y/D < 3.8$ (right and left of the epiglottis) is because of bad data in that region. Also note that the flow is blocked to the left of the epiglottis. Farther downstream, Figure 4(c) shows the formation of two recirculation regions; one behind the epiglottis
(left side) and the other one in the bottom right side of FOV3 because of the proximity of the entrance to the larynx region (see Figure 1). It is obvious that the flow in this region is directed to the entrance of the larynx region and produces a laryngeal jet. Another large-recirculation flow can also be seen in the trachea in the right side of FOV4 (see Figure 4d) that is due to the deflection of the flow by the larynx.

![Mean turbulence quantities](image)

Figure 4: Four mean velocity fields (a), (b), (c), and (d) obtained at different locations in the upper airway (see Figure 1). The flow rate is 10 l/min which yielded a $Re$ of 716. Locations $x$ and $y$ are normalised by the nozzle diameter $D$. Note that only some vectors are shown in these plots. The gray shapes in plots (b) & (c) represent a cross-section of the epiglottis and the line S-S in (b) represents the location at which some local information was extracted.

6.2 Mean turbulence quantities
This section presents results of the horizontal and vertical turbulence intensities ($u_{rms}$ and $v_{rms}$), turbulent kinetic energy $k$, and Reynolds shear stress $<uv>$. The results restricted to the pharynx region (FOV3) are presented in Figure 5. In this figure, locations $x$ and $y$ are normalised by the nozzle diameter $D$ and the velocities are normalised by the inlet velocity $U_0$. Figure 5(a) displays colour contour of $u_{rms}$, which shows that the highest turbulence intensity is located behind the epiglottis ($3.86 < y/D < 4.24$) and near the entrance to the larynx. However, the position of the highest value of the vertical turbulence intensity $v_{rms}$ shown in Figure 5(b) is slightly shifted to the right of peak $u_{rms}$ which matches the local maximum velocity in that region (see Figure 4c). In addition, the peak $v_{rms}$ occurs in a relatively thin strip parallel to the epiglottis (not shown) while the peak $u_{rms}$ is relatively thicker. Note also that there is a smaller strip of relatively high $u_{rms}$ in Figure 5(a) corresponding to the position of the peak $v_{rms}$ shown in Figure 5(b).

To summarize the behaviour of the horizontal $u_{rms}$ and vertical $v_{rms}$ turbulence intensities discussed above, the turbulent kinetic energy $k$ calculated from these components $k = 0.5(u_{rms}^2 + v_{rms}^2)$ is shown in Figure 5(c) as a colour contour. The location of the highest values of $k$ appears very
similar to the distribution of $u_{\text{rms}}$, and also consistent with the $v_{\text{rms}}$ results. This indicates that the fluctuating components $u'$ and $v'$ are correlated in this region. Generally, it seems that the region of peak $k$ (besides the epiglottis) is an active location of turbulence production.

The locations of high absolute Reynolds shear stress shown in Figure 5(d) are consistent with the previous results. This figure shows that the location of highest magnitude of $<uv>$ is concentrated in a strip (blue colour) which exactly matches the position of the peak value of $v_{\text{rms}}$. Another strip of relatively strong $<uv>$ can also be seen in this figure (dark yellow) at the left of previous strip. This result indicates that the momentum exchange by the Reynolds stress is enhanced in this region. From a quadrant analysis prospective, it seems that this region is characterised by events similar to ejection/sweep that usually occurs near solid walls. This behaviour will be briefly discussed below.

6.3 Large-vortical structures

In this section, only the results in the pharynx region (FOV3) are presented. After exposing and quantifying properties of the vortical structures as described in section 5, a statistical analysis of the distribution of vortex size and circulation was performed. Four POD modes were used for reconstruction, which recovered approximately 60% of the turbulent kinetic energy. It should be noted that vortical structures with a radius smaller than three grid units (~0.03$D$) or a circulation less than 0.1 cm$^2$/s were eliminated. It should also be noted that all the results presented in this work correspond to vortices whose axes are approximately perpendicular to the $x$-$y$ plane.

Figure 6 presents two selected examples of POD-reconstructed velocity fields. These two fields were acquired at a framing rate of 7.4 Hz. The actual time difference (1/7.4 s) was normalised by the local time scale $\sqrt{A}/U_B$, where $A$ is the local cross-sectional area at section S-S (see Figure 4b) and $U_B$ is the corresponding bulk velocity. It is found that the time difference $\Delta t$ is approximately

![Figure 6: Examples of POD-reconstructed velocity fields in the pharynx region (FOV3). The time separation between (a) & (b) is 0.31 times the local time scale calculated at section S-S shown in Fig. 4(b). Red and blue circles represent counter-clockwise and clockwise rotating structures, respectively.](image-url)
one-third of the local time scale ($\Delta t = 0.31$). Note that red and blue circles represent counter-clockwise (positive) and clockwise (negative) rotating structures, respectively, identified using the vortex identification method of Agrawal & Prasad (2002). Figure 6(a) shows several structures distributed in that region of different sizes and strengths. These structures seem to be correlated with the structures that appear in Figure 6(b). It is interesting to see that the structures that reside near the epiglottis appear stronger than the other structures distributed in the FOV. It can be observed that some parcels of fluid have higher momentum compared to the surrounding as those labelled A in Fig. 6(a) and B in Fig. 6(b). This behaviour is similar to the mechanism of ejection/sweep events. A more detailed analysis is presented below in the form of a statistical study that is based on all the vortices identified in FOV3 at a framing rate of 2 Hz (see Figure 1). This will provide deeper insight into the vortex characteristics in the flow.

The distribution of vortex radius $R$ and circulation $\Gamma$ with downstream locations $y$ is illustrated in Figure 7(a) and (b), respectively. Both $R$ and $y$ are normalised by the nozzle diameter $D$ while $\Gamma$ is normalised by $DU_o$. Note that the sign of $R/D$ in Figure 7(a) and $\Gamma/DU_o$ in Figure 7(b) corresponds to the rotational sense of the vortex, where positive value represents positive rotational sense. These plots were obtained from a set of data contained 2000 instantaneous velocity fields. It should be pointed out that the band near $R/D = 0$ corresponds to the minimum resolvable vortex size of $R/D < 0.03$. Figure 7(a) clearly shows that the flow contains vortices of sizes in the range $0.03 < R/D < 0.15$. Since the width of the pharynx region is equal to 24.4 mm, the largest vortices occupy about 47% of the pharynx width. Moreover, the distribution of positive vortical structures is almost a mirror-image of the negative ones.

Figure 7(b) shows that the circulation magnitude $|\Gamma/DU_o|$ varies from a weak (close to zero) to a relatively stronger circulation at locations in the range $3.8 < y/D < 4.3$. However, the identified vortices that reside outside this range have circulation magnitudes close to zero. Figure 7(b) illustrates that the strength of positive vortical structures increases significantly to $\Gamma/DU_o \approx 0.3$ in the range $4 < y/D < 4.2$ (near the epiglottis). This region appears to be active and the relatively high increase in the strength of positive vortices may be linked to the events similar to ejection/sweep events that were noticed in that region.

![Figure 7](image-url)

Figure 7: The distribution of (a) vortex size $R$, and (b) circulation $\Gamma$, with downstream locations $y$. These plots represent data extracted from 2000 instantaneous velocity fields. Note that positive $R/D$ and $\Gamma/DU_o$ represent counter-clockwise rotational sense.
The circulation associated with vortical structures of different sizes is shown in Figure 8. In this figure, the horizontal axis represents a normalised vortex radius \( R/D \) and the vertical axis represents the normalised circulation \( \Gamma/\text{DU}_e \). Note that the sign of the vortex radius \( R \) corresponds to the rotational sense of the vortices. The purpose of this plot is to show the variation of the vortex strength with vortex size. This figure confirms the earlier observation of the high increase of the strength of positive vortices \( (\Gamma/\text{DU}_e \approx 0.3) \) which takes place near the epiglottis. This result explains the relatively high turbulence intensities and Reynolds stress in that region. In addition, it is interesting to see that the large increase in the positive vortex strengths is not accompanied by a corresponding increase in vortex sizes in that region, obviously because of the flow boundary. However, the range of the negative (clockwise) vortex sizes appears relatively larger than the range of the positive structures for \( |\Gamma/\text{DU}_e| < 0.15 \).

![Figure 8: Distribution of normalised circulation \( \Gamma/\text{DU}_e \) associated with the identified vortices of different sizes for FOV3.](image)

### 7. Conclusions

PIV measurements have been made at four locations in the ETA model at a flow rate corresponding to 10 l/min in the prototype yielding a Reynolds number \( Re \) of 716. The following conclusions may be drawn from the analysis of the mean flow and POD results:

- The shear layer emanating from the leading edge of the epiglottis is unstable,
- The region near the epiglottis in the pharynx is characterised by events similar to wall-region ejection/sweep events, and
- Although the size of the counter-clockwise and clockwise vortices identified in the pharynx region appear to almost identical, the counter-clockwise structures appear to be much more energetic which suggests high kinetic energy and momentum exchange in that region.

Finally, those data presented represent only a small slice of what is clearly a highly three-dimensional flow field; investigations continue to explore the complex flow in the posterior-anterior
plane of the ETA.

Acknowledgments

The support of the Natural Sciences and Engineering Research Council (NSERC) of Canada is gratefully acknowledged. The authors thank Stan Prunster, a technician in the Department of Civil Engineering at Queen’s university, for providing equipment during the making of the ETA model.

References