Visualization of nasal airflow patterns in a patient affected with atrophic rhinitis using particle image velocimetry

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Abstract. The relationship between airflow patterns in the nasal cavity and nasal function is poorly understood. This paper reports an experimental study of the interplay between symptoms and airflow patterns in a patient affected with atrophic rhinitis. This pathology is characterized by mucosal dryness, fetor, progressive atrophy of anatomical structures, a spacious nasal cavity, and a paradoxical sensation of nasal congestion. A physical replica of the patient’s nasal geometry was made and particle image velocimetry (PIV) was used to visualize and measure the flow field. The nasal replica was based on computed tomography (CT) scans of the patient and was built in three steps: three-dimensional reconstruction of the CT scans; rapid prototyping of a cast; and sacrificial use of the cast to form a model of the nasal passage in clear silicone. Flow patterns were measured by running a water-glycerol mixture through the replica and evaluating the displacement of particles dispersed in the liquid using PIV. The water-glycerol flow rate used corresponded to an air flow rate representative of a human breathing at rest. The trajectory of the flow observed in the left passage of the nose (more affected by atrophic rhinitis) differed markedly from what is considered normal, and was consistent with patterns of epithelial damage observed in cases of the condition. The data are also useful for validation of computational fluid dynamics predictions.

1. Introduction

Recent years have witnessed a surge of interest in the application of scientific methods to the study of flow in the human nasal passage. This is not to belittle the pioneering work that was done by the likes of Paulsen [1] and Franke [2] in the late 19th century, or Masing [3] and Swift and Proctor [4] in the second half of the 20th century. Nevertheless, technological developments have made possible higher resolution and non-invasive investigations of nasal flow, and research groups have been quick to take up the opportunities offered. Three developments have proved to be particularly serendipitous: (a) Particle Image Velocimetry (PIV) has allowed the non-invasive measurement of three-dimensional velocity fields; (b) the three-dimensional printing techniques associated with rapid prototyping have made it possible to construct anatomically faithful models of nasal passages derived from Computed Tomography (CT) scans; (c) the capability of Computational Fluid Dynamics (CFD) to predict accurately flows through geometrically complex passages has generated huge interest in modelling of patient-specific nasal flows.

Historically, it was CFD that led the way: the ease and relatively low cost with which models could be generated made this route very attractive. However, numerical predictions require validation, i.e.
experimental measurements must be made. The small size of the nasal passages limit in-vivo measurements of flow patterns, while measurements in cadaveric heads are inaccurate due to the physiological changes that accompany death and occasionally the replacement of anatomical structures with glass plates [3,4]. Moreover, the strength of the validation process is enhanced by the degree of similarity between the geometries used in the numerical and physical experiments. Three-dimensional printing techniques meet this need: they can generate experimental models derived from the same CT scans as used for the CFD study, thus ensuring the highest possible degree of geometrical similarity. Given a physical model, the problem still remains as how to measure flow through the model. Using water as the working fluid, typical techniques include flow visualisation via streams of neutrally buoyant dye, and measurement of integral quantities such as trans-nasal pressure drop. Measurement of velocities inside the model is more problematic. The introduction of hotwire anemometry probes is possible [5, 6], but the method is invasive (it changes the flow being measured), and is limited to application to a few points in the flow. Laser doppler velocimetry (LDV) is better, being non-invasive; it also allows the sequential acquisition of series of data from the flow. The disadvantages of LDV are that it is time consuming to set up and requires an optically clear model. PIV carries the same overhead as LDV (set up time and optical clarity of the model), but once these issues have been addressed, it allows a much more rapid and detailed assessment of the flow field.

This paper addresses the application of PIV to the investigation of flow in a nasal model. The experimental work is one element of a much larger programme of research that includes the use of CFD. The results of the numerical work are described elsewhere [7, 8]. The nasal model studied in this paper has been derived from a CT scan of an adult male suffering from the condition of atrophic rhinitis (AR) [9, 10]. In this condition, the nasal cavity is unusually patent on account of the virtual disappearance of the subject’s turbinates. Turbinates are shelf-like structures that hang down from the lateral wall of the nasal cavity, resulting in an increase in the surface area of the cavity; this provides for increased heating and humidification of air breathed in, and a greater surface area upon which to capture and remove inspired particles that might be harmful to the respiratory system. AR results in excessive drying of the nasal mucosa which becomes susceptible to disease; perversely, although the passage is abnormally patent, the subject is likely to complain about the sensation of nasal blockage. AR is ideally suited to experimental and numerical investigation so as to enhance the clinical understanding of the condition.

2. Apparatus and Experimental Method

2.1. The nasal cast
A 26-year-old Caucasian male suffering from AR was recruited to this research project. CT scans were taken with a resolution of 0.146 mm × 0.146 mm × 0.600 mm. The scan extended from the tip of the external nose to the post-nasal space; this was considered important so as to maintain as much realism as possible in the conditions at the inflow to and outflow from the model.

The scans were imported to the imaging software Mimics™, and edited to remove unwanted detail such as sinuses. A three-dimensional reconstruction of the nasal passage was generated and an “airbox” was created around the external nose, Figure 1. The geometry was then exported as an STL file suitable for three-dimensional printing. A Z-Corporation rapid prototyping machine was used to create a three-dimensional negative of the nasal passage in a water soluble material. The model was printed full scale. The negative of the passage was placed in a rectangular plexiglass box and surrounded with a transparent liquid silicone; after 48 hours of curing, the model was washed out, leaving the positive image of the passage in the silicone. However, since the water-soluble model would be permeable to the liquid silicone, it was necessary to coat the model with a barrier material prior to pouring the silicone. Following Hopkins et al. [11], the model was painted with several layers of a water-soluble glue. Care was required because of the fragility of the model, and its flexibility when moistened by the glue. Once the water-soluble material was washed out of the silicone, small inclusions that remained were removed by using surgical instruments. The accuracy of the silicone
replica was checked by acquiring CT scans of the replica, re-constructing the nasal volume in 3D using Mimics™, and comparing this 3D reconstruction to the original nasal geometry. As illustrated by Figures 1 and 2, the result was deemed satisfactory. Figure 2 shows a photograph of the final cast. The optical clarity of the model when filled with the working fluid (see §2.2) was better than that suggested by Figure 2. In particular, although the optical clarity in the region of the external nose does not appear as good as in the rest of the cavity, accurate measurements were obtained in the whole domain.

Figure 1. Sagittal view of reconstructed nasal cavity from right hand side.

Figure 2. Sagittal view of silicone cast from right hand side.
2.2. The flow rig
The flow rig (Figure 3) comprised a header tank, attached via standard 32 mm diameter plastic piping to the model and a sump. A valve between the model and the sump was used to control the flow rate. The working fluid was manually returned to the header. The total head in the reservoir was 2.5 m. The flow rate was measured using a graduated cylinder and a stopwatch.

To minimize optical distortion, the working fluid was a mixture of 54% glycerol and 46% water. At ambient conditions (20°C), this mixture has a density of $1.14 \times 10^3$ kg/m$^3$ and a kinematic viscosity of $8.84 \times 10^{-6}$ m$^2$/s [12]. The experiment was run with a constant flow rate of 200 ml/s. Reynolds number matching with physiological conditions (steady breathing of air at standard atmospheric conditions) shows that this is dynamically similar to breathing 343 ml/s which is typical of resting breathing for healthy adult males.

![Figure 3. Experimental setup showing the flow rig, the nasal replica, the laser, the CCD camera, and the computer.](image)

2.3. Particle Image Velocimetry
The PIV equipment used was supplied by LaVision Gmbh. It comprised: (a) a Flowmaster 2S CCD camera with a resolution of 2048 × 2048 pixels and a maximum frame rate of 15 Hz; (b) a double pulsed Nd:YAG laser emitting light at a wavelength of 532 nm; and (c) a PC running the LaVision DaVis 7 software. The seeding particles (Sphericel 110P8, from Potters Industries Inc.) were hollow glass spheres with mean diameters of 9-13 μm. The seeding particles had a density of $(1.10 \pm 0.05) \times 10^3$ kg/m$^3$, making them nearly neutrally buoyant in the glycerol/water mixture.

Measurements were made in a series of coronal and sagittal planes spaced at 5 mm and 2 mm, respectively, amounting to about 18 planes in each direction. Data acquisition started 20 seconds after the flow control valve was opened and lasted for approximately 20 seconds. For each cross-section, 50 double frame images were acquired. The time step between the two frames varied from 50 to 400 μs and was adjusted for each cross-section so that particles traveled an average distance of 4 to 8 pixels between the two frames. Instantaneous velocity fields were calculated using a multi-pass cross-correlation algorithm and a median filter to remove spurious vectors. The data presented here are averages of these 50 snapshots of the velocity field. A Fortran program was written to translate the
PIV data from Davis format to PLOT 3D format, which was then imported to the postprocessing software Fieldview™.

2.4. Sources of error
Three quantifiable sources of error are identifiable in the experimental set up:
(a) pixel size could be estimated with an accuracy of 95%;
(b) displacement vectors could be calculated to within 0.1 pixel. Given that the frame rate was chosen to allow particles to travel typically 4 pixels between images, this equates to an error of 2.5% in the velocity vectors;
(c) the flow rate could be measured to within 5% using the graduated cylinder.

In addition, small inclusions of air in the internal surface of the model caused scattering of the laser light that endangered the CCD camera. These were dealt with by placing black dots over the outer surface of the silicone replica using a marker pen. The inclusions were limited to very small regions in the turbinates and the external airbox (Figure 4).

Finally, the flexibility given to the negative of the nasal cast when moistened with its coatings of barrier glue caused some distortion relative to the original model. The extent of this deviation was evaluated by calculating the surface area and volume of the physical replica and comparing these numbers to their counterparts in the original geometry. A good match was observed; the surface area and the volume of model were, respectively, 85% and 99% of their original values.

3. Results
The velocity vectors in the sagittal planes show distinctly different flow patterns on the left and right sides. In the left, more patent side, the flow meets no obstacles as it enters the passage and rises proximally towards the olfactory region (Figure 4(a)). In contrast, on the right cavity, the anterior passage is restricted proximally due to a septal deviation; consequently the flow follows a path closer to the floor of the passage, which is more characteristic of a normal case. In coronal planes, the flow is again seen to be distinctly different in each cavity. While large secondary flow is observed in the left side, with a clear clockwise rotation (as seen from the nostrils), there is much less displacement of fluid in the coronal planes in the right (Figure 4(b)).

4. Discussion
Experimental and computational investigations of nasal airflow during the last century have characterized the normal patterns of nasal airflow in healthy adults. Multiple investigators have reported that the main air stream passes near the nasal septum, with lower flow rates through the olfactory slit and the nasal meatuses [5,13-15]. This airflow distribution changes little when the flow rates increase from breathing at rest to breathing during exercise. In contrast to what is known for healthy individuals, nasal airflow patterns in abnormal nasal geometries (e.g., pathological or altered through a surgical intervention) are still largely unknown.

The air flow patterns in the left side of the AR nose studied here are quite abnormal. This finding may have important clinical implications. For instance, the shift in the trajectory of the main air current means that the main epithelial regions responsible for warming and humidifying inspired air are different in the left passage of the AR patient as compared to the patient’s right passage and other normal passages. In healthy noses, the normal flow patterns imply that atmospheric air is warmed and humidified mainly in the antero-inferior portion of the nasal passages [8]. In contrast, inspired air comes in close contact with the nasal mucosa of the mid to upper regions of the atrophic nose. Consequently, it is inferred that the heat and water fluxes along the upper half of the AR nose are higher than in normal individuals [8]. This might explain the clinical observation that crusts are usually confined to the middle and superior turbinates (as opposed to the inferior turbinate) in the early stages of the disease [16].

A multitude of CFD papers on nasal airflow has been published in recent years, but very few experimental data are available to confirm the computational results. As shown here, an anatomically-
accurate nasal replica can be created through rapid prototyping techniques. When used in combination with the PIV technique, the velocity fields in the nasal passages can be described in detail. This methodology provides a valuable means of validating predictions of CFD models of nasal airflow. A comparative study of the PIV data reported here to CFD predictions for the same nasal geometry is presently in preparation [7].

![Figure 4. Velocity vectors in (a) a sagittal plane through the left cavity and (b) a coronal plane in the position indicated in (a). The black region on the left marks an area where data could not be collected due to the high intensity of light reflections.](image)

5. Conclusions
A three-dimensional silicone cast of the nasal cavity of a patient affected with atrophic rhinitis was successfully constructed. The nasal cast was used in Particle Image Velocimetry experiments to investigate the airflow patterns in AR. The results revealed very different flow patterns in the right and left cavities. In the less patent side, air was forced to flow mainly along the floor of the nose by an anterior septal deviation. In contrast, the main air current passed through the upper half of the wider side, with a low-velocity vortex present on the floor of the nose. These abnormal patterns of airflow are likely associated to some symptoms of AR, such as the preferred formation of crusts in the middle and superior turbinates (in opposition to the inferior turbinate).

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