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Surface mapping for visualization of wall stresses during inhalation in a human nasal cavity

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ABSTRACT

Airflow analysis can assist in better understanding the physiology however the human nasal cavity is an extremely complicated geometry that is difficult to visualize in 3D space, let alone in 2D space. In this paper, an anatomically accurate 3D surface of the nasal passages derived from CT data was unwrapped and transformed into a 2D space, into a UV-domain (where *u* and *v* are the coordinates) to allow a complete view of the entire wrapped surface. This visualization technique allows surface flow parameters to be analyzed with greater precision. A *UV*-unwrapping tool is developed and a strategy is presented to allow deeper analysis to be performed. This includes (i) the ability to present instant comparisons of geometry and flow variables between any number of different nasal cavity models through normalization of the 2D unwrapped surface; (ii) visualization of an entire surface in one view and; (iii) a planar surface that allows direct 1D and 2D analytical solutions of diffusion of inhaled vapors and particles through the nasal walls. This work lays a foundation for future investigations that correlates adverse and therapeutic health responses to local inhalation of gases and particles.

1. Introduction

The fluid dynamics behavior and physical interactions between the surface wall, inhaled air and particles all occur simultaneously during inhalation. Visualization of fluid and particle flow during inhalation can provide insight and a better understanding into the physics involved in respiration. During nasal inhalation, moving air passing over the nasal cavity walls creates a shearing of the fluid producing airflow-induced mechano-physical stress in the form of a wall shear stress (Elad et al., 2006). Recent WSS mapping on surface walls in hemodynamic studies have helped establish causative-effect relations in understanding morphology and risk assessments of aneursyms (Goubergrits et al., 2012; Reneman et al., 2006). Similarly, such mappings can assist in understanding the link between the complex nasal morphology and its physiological functions, which contribute toward many current research fields including nasal surgery (Kim et al., 2013; Rhee et al., 2011), particle inhalation and its toxicology (Inthavong et al., 2009), and physiological function (Elad et al., 2008; Lee et al., 2010).

Doorly et al. (2008) analyzed the effect of flow instability on wall shear stress (WSS), by mapping out the WSS occurring along the perimeter of one cross-sectional slice. The profile was taken along the cross-sectional perimeter slice which means that WSS profiles can only be viewed along the specified slices. Using this method would be difficult in displaying many possible WSS profiles along the perimeter of cross-section slices to map out the entire cavity wall. An alternative is to display a WSS contour over the 3D domain. This would allow a qualitative result that can reveal local concentrated stresses. However the representation of 3D model results is limited to digital media where software is needed to rotate the model to obtain the desired view. Even under this method, not all surfaces can be viewed adequately, with ease.

An alternative is to transform the 3D model into a 2D representation by the *UV* mapping technique used in computer graphics. The letters *U* and *V* denote the coordinate axes of the 2D plane while *X*, *Y*, *Z* are retained in the coordinate axes of the 3D object. The 2D map provides an overview of the entire geometry, where both septal and lateral wall surfaces can be plotted simultaneously – a feature that is prohibitive in 3D models. The *UV* mapping is highly effective for reporting results in 2D format, e.g. paper reports.

Furthermore a recurring theme emerging from recent studies of nasal inhalation (Abouali et al., 2012; Chung and Kim, 2008; Na et al., 2012; Wen et al., 2008; White et al., 2011; Zhu et al., 2011) is the differences found in nasal morphology between individuals which has been attributed to age, sex, and ethnicity (Churchill et al., 2004). Intra-individual differences are also found between the structure of the left and right nasal airways, as well as temporal variations caused by nasal cycling

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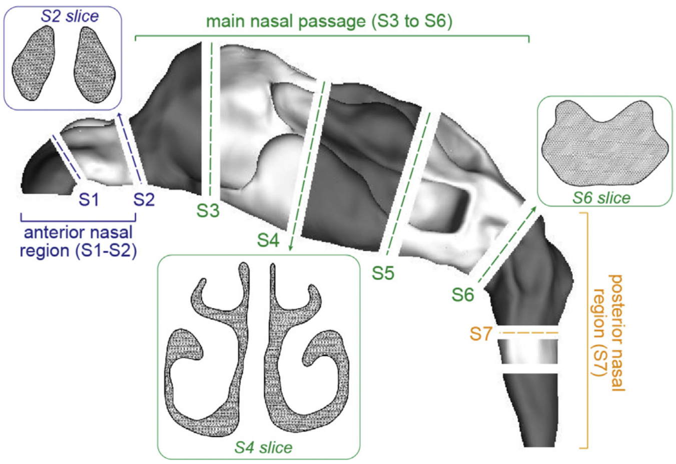

Fig. 1. Nasal cavity geometry with sectioned slices, labeled as S1–S7. Three cross-sections are shown taken at S2, S4, and S6.

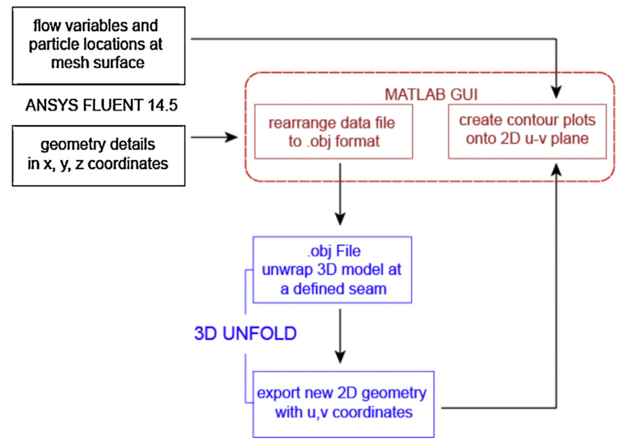

Fig. 2. Flow chart showing the conversion process of a 3D nasal cavity geometry into a 2D surface representation.

(Eccles, 1996). Recently a single representative model of the human nasal cavity was produced by Liu et al. (2009) based on measurements of 30 sets of computed tomography (CT) scans of nasal airways was created, while Gambaruto et al. (2012) presented an averaged geometry using Fourier descriptors and medial axis transforms of cross-sectional slices of three nasal cavities.

In this study, a *UV*-unwrapping strategy and data management and analysis tool is developed to allow new methods of respiratory flow analysis and direct comparisons between different models. The *UV* unwrapping approach allows (i) the ability to present instant comparisons of geometry and flow variables between any number of different nasal cavity models through normalization of the 2D unwrapped surface; (ii) visualization of an entire surface in one view and; (iii) a planar surface for direct 1D and 2D analytical solutions of diffusion of inhaled vapors and particles through the sub-nasal walls. An executable program for data management and analysis is developed as part of the unwrapping methodology and this is available online at www.cfdresearch.com/matlab-2/uv-unwrapping-tool/. This work lays a foundation for future investigations that incorporates toxicology and health responses to local inhalation of gases and particles by creating additional *UV*-layers underneath the unwrapped surface map that represents the sub-nasal wall layers, e.g. mucus, tissue, and blood layers.

2. Method

2.1. Computational model

A computational fluid dynamics (CFD) model of a human nasal cavity obtained through CT scans from a healthy 25-year old, Asia male (170 cm height, 75 kg mass) has been created (Inthavong et al., 2011a) and for brevity the details of its model construction and verification can be found in Inthavong et al. (2009) and Wen et al. (2008). Grid independence was tested and the mesh was refined in the near wall and regions of high curvature. The nasal cavity was meshed with unstructured tetrahedral cells (3.7 million cells, 318 MB in computational memory size) with 10 prism layers attached on the wall using a HPxw6600 16 Gb RAM, 8 processor workstation. For turbulent flow regimes, typically for flow rates greater than 20 L/min the maximum y^+ value was in the order of 10^{-1} ($y^+_{\max} = 0.48$).

The computational model was divided into eight sections, by seven slices and labeled as S1–S7 (Fig. 1). The regions S1 and S2 are contained in the anterior third with S2 slicing through the nasal valve region, S3–S6 are in the main nasal passage which displays the turbinate intrusions into the airway and the well-defined septal walls, while S7 is in the posterior third containing the airway curvature into the nasopharynx. Two straight extension pipes, one at the inlet, and one at the outlet were created into the geometry to satisfy a fully developed flow assumption, each having a length of ten times its diameter.

2.2. UV-unwrapping

The flow process of converting a 3D model to 2D surface is outlined in a flow chart given in Fig. 2. The data containing information regarding the 3D nasal cavity geometry from Ansys-Fluent CFD commercial software is outputted as an *ascii* file format and accessed through Matlab. The data is rearranged so that it conforms to the .obj file format. This allows the data to be read into an open source (Blender, Blender Foundation) or commercial (3D Unfold, Polygonal Design, France) 3D modeling software. Within the software, the 3D model is unwrapped at a defined seam based on the ISOMAP algorithm (Tenenbaum et al., 2000). The converted 2D geometry with new coordinates in the *U–V* domain is exported back into Matlab and is coupled with solution data obtained from CFD in the form of the flow variables and particle deposition. A Matlab graphical use interface (GUI) is developed as shown in Fig. 3 to act as an intermediary function to couple the two separate sets of data.

Graphically Fig. 4 presents the flow process. First the nasal cavity is divided into the left and right chambers. Each chamber is then unwrapped by creating a cutting slice along the bottom of the geometry to create a common reference boundary in which the surface coordinates can be related to. This common boundary edge is separated by the inlet and outlet of the nasal chamber. Furthermore the selection of the nasal floor ensures correct topology in the *UV*-domain for regions of overlapping geometry such as that found in the meatus airway.

2.3. Flow modeling and boundary conditions

The geometry and mesh were inputted into a commercial CFD software, Ansys-Fluent v14.5, where the governing equations for fluid flow were modeled, to simulate the steady flow field in nasal