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Investigation of flow characteristics in regions of nasal polypoid change

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A B S T R A C T

We used computational fluid dynamics to study the airflow characteristics in the ostiomeatal complex/middle turbinate of the human upper airway, where clinically relevant nasal polypoid changes occur (designated Regions A1–A4). We assessed six different flow rates representing one full period of respiration, based on realistic human respiration data, in an anatomically correct numerical model of a patient with a history of polypectomy.

The simulation results showed that Regions A1–A4 were not correlated with the local stagnation points where a locally high level of wall pressure was achieved. They, however, exhibited a very distinctive feature in that the positive wall-normal pressure gradients evaluated at the epithelial surface were persistent at six different flow rates spanning the whole respiration period in these areas. Therefore, the regions where polypoid changes developed were thought to be subject to mechanical irritation of the epithelium constantly via locally accelerating airflow moving towards the surface from the airway. On the contrary, relatively large or small values for local wall shear stress were not correlated with Regions A1–A4.

1. Introduction

Nasal polyps (NPs) are commonly observed benign lesions arising from the mucosa of the nasal cavity, which affect up to 4% of the population [1–4]. They generally produce symptoms such as nasal obstruction, mucosal swelling, headache, and various infections, with the affected patients frequently complaining of watery rhinorrhea and postnasal drip [1–4]. Anosmia or hyposmia are other typical symptoms of polyps [3,5].

The etiology of NPs is not well known, although it has been linked to many clinical conditions such as chronic infection, drug sensitivity, epithelial disruption, epithelial cell defects, and alterations in the nasal aerodynamics due to the trapping of pollutants [2,3,6]. Recent clinical data indicate that the association of NPs with asthma is well recognized [2–4,7], while the role of allergies in the etiology and pathogenesis of NPs is still controversial [3,4,6,8–11]. Despite numerous studies on the pathogenesis of NPs, the initiating causes remain unknown, suggesting that various mechanisms might exist in different cases.

Many studies have provided comprehensive information regarding the sites of NP formation. Despite the presence of a relatively wide individual variation in the anatomy of the nasal cavity, the ostiomeatal complex (or anterior ethmoid complex [12]) is reported to be the most frequent site of NP formation [11,13–19]. In particular, Stammberger [13] observed that the rate of occurrence of NPs is over 80% in the regions of the uncinate process, middle turbinate, and infundibulum, which was later confirmed by Assanassen and Naclerio [14] and Andrews et al. [17]. Interestingly, Stammberger [13] noted that the areas at which NPs frequently originate are situated where the airstream first comes into contact with the mucosal surfaces, which might indicate that the presence of a nearby stagnation region resulting from the collision of the approaching airflow with the protruding surface of the epithelium is one of the discernable features of the regions of frequent NP formation.

The existence of regions with common high rates of NP formation, such as the uncinate process, middle turbinate, and infundibulum, observed by many independent groups of clinicians might suggest the conjecture that the local physiological characteristics strongly influenced by the anatomical geometry of these regions are better correlated with NP formation than the other intrinsic clinical conditions of an individual. Although the literature suggests that various local physiological factors trigger NP formation, it is important to assess the common features of local airflow in the regions with NPs that directly reflect the local geometric characteristics such as those described by Stammberger [13], in order to enhance our understanding of the possible role of airflow in NP formation.

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The aim of the present numerical work was to examine the airflow characteristics in the regions where NPs occur, in order to investigate the presence of any distinctive canonical airflow features that might be considered as influencing the formation of NPs. In particular, the surface force exerted on the epithelium of the airway by local flow through the action of both wall pressure and wall shear stress was assessed. To achieve this, an anatomically correct numerical domain based on the computed tomography (CT) data of a male patient with a history of polypectomy was constructed to model the nasal cavity.

2. Numerical methodology

2.1. Construction of a numerical domain

A computational model of the nasal cavity was created using 0.65-mm-thick CT images of a 45-year-old male patient who experienced recurrent NPs. The patient had a history of polypectomy for the surgical removal of an NP formed in the middle turbinate in December 2003. He underwent an endoscopic procedure and CT for the treatment of recurrent nasal obstruction in May 2013. At this time, the patient was found to be free of any NPs (Fig. 1a). However, he was later diagnosed with several polypoid changes in the free margins of the uncinate process and middle turbinate and the anterior portion of the middle meatus in July 2013 (Fig. 1b), upon which the patient started receiving medical management. Note that the viewing angle and position of the endoscope are not the same for the two images taken at different times, shown in Fig. 1. In order to study the local flow characteristics in the region where polypoid changes had formed, a nasal cavity model was created using the CT data of the patient acquired in May 2013. The CT images were acquired at the Samsung Medical Center in Korea, and approval for this study was obtained from the Institutional Review Board (IRB) of the Samsung Medical Center.

Within the nasal cavity model created using the CT data obtained in May 2013 (Fig. 2a), four different regions – Regions A1, A2, A3, and A4 – were selected corresponding to the locations where the nasal polypoid changes actually appeared in the later CT images acquired in July 2013. These regions were found to be located in the ostiomeatal complex, which is reported to be the most frequent site of NP formation [11,13–19]. The axial view of the CT image shown in Fig. 2b indicates that Regions A2–A4 had common geometric features in that the collision of the approaching airflow with the protruding surface of the epithelium occurred nearby, as noted by Stammberger [13]. On the other hand, Region A1 was located in the trough region of the lateral wall.

A series of steady computations were performed at several flow rates during both the inspiration and expiration periods in the human nasal cavity model shown in Fig. 3, in order to examine the air flow characteristics in the regions with NP formation. In order to reduce the computational costs, the main bodies of the various paranasal sinuses, including the maxillary and ethmoidal sinuses, were excluded in this nasal cavity model.

To achieve sufficiently accurate numerical results for the regions which had a relatively large velocity gradient, the grid-generating software ANSYS Meshing v14.5 (Pennsylvania, USA) was used to generate meshes with combined tetrahedral and prism elements (Fig. 3). As in our previous studies with similar geometry, seven layers of prism meshes were placed near the cavity surface [20,21]. The findings of the previous studies [20,21] had revealed that the use of approximately 4 million meshes is adequate for capturing the significant flow characteristics; we, therefore, assumed that computations conducted with approximately 4,008,000 mesh elements would be adequate to reveal the important flow characteristics within the scope of the present study. The justification for the use of a grid resolution of approximately 4,008,000 meshes for the present cavity model is included in Appendix A. The air chamber was placed outside the nostril, as in the study by Chung et al. [21], and the inlet boundary conditions with stagnation properties were specified at the surface of the air chamber.

2.2. Selection of flow rates

For the purpose of reducing computational costs, we assumed that the real respiration process was reasonably represented by a series of steady solutions at the varying flow rates of 120, 250, and 450 mL/s during both inspiration and expiration. These flow rates effectively represented a series of instants at 0.15, 0.25, 0.49, 1.09, 1.46, 1.57, 1.67, 1.72, 1.85, 2.03, 2.70, and 3.29 s during one full respiration period of 4 s, as shown in Fig. 4, which matched the human respiration data presented by Murray and Nadel [22] and constructed by Chung et al. [21]. Each flow rate was produced by applying an appropriate relative pressure difference between the inlet and the outlet of the numerical domain in order to mimic the natural respiration process, in a similar manner to that performed by Chung et al. [21].

The flow regime in the nasal cavity depends on specific airflow rates. Doorly et al. [23] observed turbulences in steady analyses at flow rates over 25 L/min (≈ 417 mL/s). Therefore, we decided that

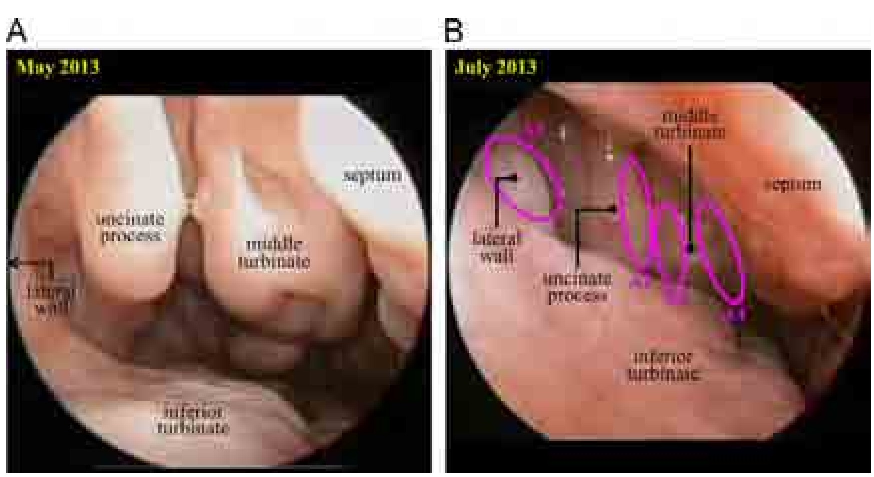

Fig. 1. Endoscopic images of the patient. (a) Endoscopic image acquired in May 2013. (b) Endoscopic image acquired in July 2013 showing four polypoid changes in the ostiomeatal complex.

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