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Assessment of airflow ventilation in human nasal cavity and maxillary sinus before and after targeted sinonasal surgery: A numerical case study

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ABSTRACT

In this study, we evaluated the effects of targeted sinonasal surgery on nasal and maxillary sinus airflow patterns. A patient, who underwent right balloon sinuplasty and left uncinectomy for recurrent maxillary sinus barometric pressure, and concomitant septoplasty and bilateral inferior turbinate reduction for deviated nasal septum and inferior turbinate hypertrophy, was selected. Two 3D models representing both pre- and post-operative sinonasal morphology were constructed. The models were then used to evaluate nasal and maxillary sinus airflow patterns during respiration at ventilation rates of 7.5 L/min, 15 L/min and 30 L/min using computational fluid dynamics. The results showed that septoplasty and inferior turbinate reduction increased the nasal volume by 13.6%. The airflow patterns in the nasal cavity showed reasonably decreased resistance and slightly more even flow partitioning after the operation. Maxillary sinus ventilation significantly increased during inspiration in the left sinus after uncinectomy, and during expiration in right sinus after balloon sinuplasty. This study demonstrates computational fluid dynamics simulation is a tool in the investigation of outcomes after targeted, minimally invasive sinonasal surgery.

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1. Introduction

Human maxillary sinus, as shielded by the surrounding structures such as uncinate process, turbinates and ethmoid cells, is difficult to be physically evaluated and surgically intervened. However, sinus diseases such as chronic rhinosinusitis may cause insufficient drainage of sinus mucus and induce concurrent inflammation, obstruction of sinus ostia and nasal obstruction, which require endoscopic sinus surgery (ESS) treatment. The technical philosophy of ESS includes protection or enlargement of sinus ostia and elimination of the surrounding mucosal contact areas (Kutluhan et al., 2011).

Quite a few ESS procedures have been introduced for the treatment of maxillary sinus diseases, such as middle meatal antrostomy, balloon sinuplasty and uncinectomy. However, the effects of ESS on nasal and sinus ventilation, and sinus drainage are still unclear. For example, whether the middle turbinate shall be preserved or resected during ESS is not yet concluded (Gulati et al., 2010). Albu and Tomescu (2004), by analyzing 133 patients who underwent endoscopic ethmoid surgery and middle meatal antrostomies, reported that the size of the middle meatal antrostomy had no influence on the outcome of the endonasal surgery for chronic rhinogenic maxillary sinusitis. Kutluhan et al. (2011), by studying 20 patients who underwent either uncinectomy or natural ostial dilatation, evaluated the effects of these two procedures on maxillary sinus ventilation. They observed that uncinectomy and natural ostium dilatation were equally effective in decreasing maxillary sinus CO_2 tension (the partial pressure of CO_2), while the sinus pressure significantly decreased during inspiration after uncinectomy.

Recently, with the development of computer resources and numerical methods, simulations of models constructed from high-resolution clinical CT or MRI scans have been validated and implemented to evaluate airflow patterns in human upper airways (Segal et al., 2008; Weinhold and Mlynski, 2004). Using Computational Fluid Dynamics (CFD), the effects of accessory ostia (AO) on maxillary sinus ventilation have been investigated (Hood et al., 2009; Na et al., 2012; Zhu et al., 2012). The existence of AO can increase the sinus ventilation by at least an order larger compared to sinuses without AO. The effects of ESS (Chen et al.,

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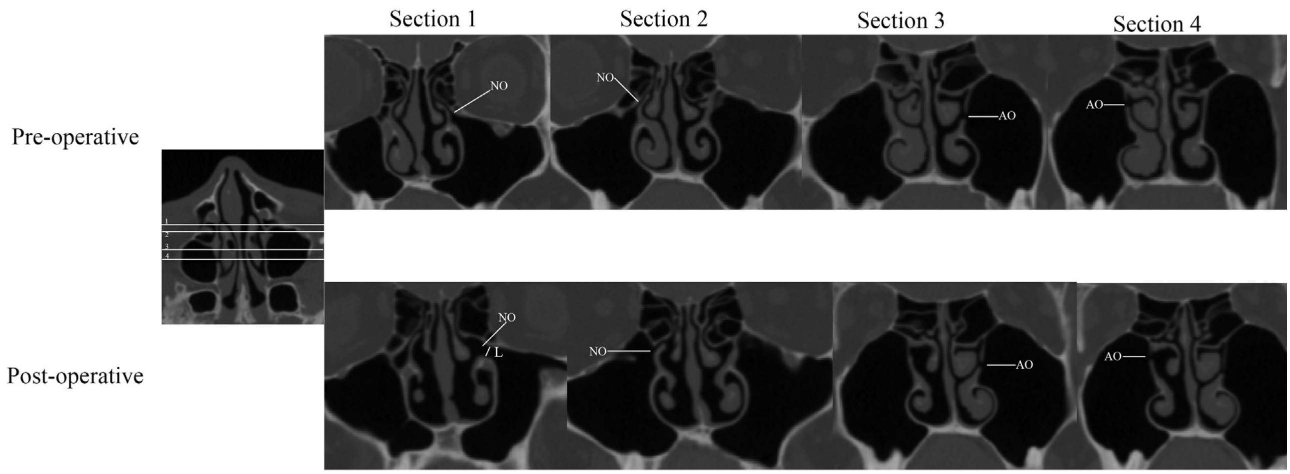

Fig. 1. Original CT of pre- and post-operative conditions. Beside natural ostium (NO), accessory ostium (AO) was found on both left and right sides and in both pre- and post-operative conditions.

2011; Xiong et al., 2008) and radical sinus surgery (Lindemann et al., 2005) on nasal and sinus airflow patterns were also studied. The sinus ventilation greatly depends on the course of the nasal airflow patterns. Although quite a few numerical works have been done on the effects of septoplasty and inferior turbinate reduction on nasal airflow patterns (Chen et al., 2009; Moghadas et al., 2011; Ozlugedik et al., 2008; Wexler, 2005), the potential effects of septoplasty and inferior turbinate reduction on sinus ventilation have rarely been evaluated. Particularly, the influence of combined sinonasal operations on nasal and sinus airflow patterns is more unpredictable but crucial to the patients' sinonasal functions.

Therefore, in the current study a subject who has undergone sinus operations on both-sides of the nasal airway, as well as septoplasty and bilateral reduction of inferior turbinates, was recruited. Two three-dimensional nasal models were reconstructed from computerized tomography (CT) scans of the subject, both before and after the surgery. Respirations corresponding to ventilation rate of 7.5 L/min, 15 L/min and 30 L/min were simulated and evaluated in these two models using CFD simulation.

2. Methodology

2.1. Patient specification

A patient who had undergone balloon sinuplasty and uncinectomy was recruited. CT scans of both pre- and post-operative conditions were obtained. The scans were taken without nasal decongestion. The pre-operative scans were processed 3 months before the surgery, and the post-operative scans were processed 7 months after the surgery. As shown in Fig. 1, uncinectomy was carried out on the left maxillary sinus and balloon sinuplasty was carried out on the right maxillary sinus. Besides natural ostia, an accessory ostium (AO) was found on both maxillary sinuses. Septoplasty and bilateral reduction of inferior turbinates had also been performed to restore the air space in the nasal cavity. As shown in Table 1, the widths of both left and right NOs have been much increased after the operation with the widths of AOs remained the same.

Table 1
Width of the air space beside uncinate process (indicated by letter *L* in Fig.1).

		NO left	NO right	AO left	AO right
Length *L* (mm)	Pre	0.66	0.56	1.37	1.88
	Post	2.94	1.14	1.38	1.84

2.2. Model reconstruction

The same process as reported in our previous study was carried out to reconstruct and discretize the models from CT scans using Mimics (Version 12.1, Materialise n.v., Leuven, Belgium) and Hypermesh (version 10.0, Altair Engineering, Inc., MI, USA) (Zhu et al., 2012). Fig. 2A shows the reconstructed 3D model of the nasal cavity. A 45 mm-radius hemi sphere was integrated around the human face representing for prescribed atmospheric pressure acting on the surface. Velocity magnitude was applied in the pharynx. Fig. 2B shows the cross sections along the turbinates. Before the operation, the right air space was quite smaller compared to the corresponding left air space due to the patient's nasal septum being mainly deviated toward his right air space/nasal cavity. After the operation, the size of the right airway is comparable to the left airway in the anterior and middle region along the turbinates, while smaller than the left airway in the posterior region. The CSAs along the turbinates were generally increased after the operation (Fig. 2C). Table 2 presents the volumes of left and right airways. After the surgery, the volume of the left airway decreased from 17.07 ml to 13.70 ml, while the volume of the right airway increased from 9.73 ml to 16.74 ml. The total volume of the nasal airways increased by 3.64 ml. The decreased left nasal volume (with concomitant increased right nasal volume) was possibly due to the septoplasty. Fig. 3 shows the reconstructed maxillary sinuses. The shape and size of the pre- and post-operative sinuses are similar, except for the air space around NOs which had been enlarged after the operation. The sizes of accessory ostia were similar between pre- and post-operative conditions since the accessory ostia were untouched during the surgery. The surfaces of hemi sphere and human face were discretized with 1.5 mm triangular elements, and the surfaces of nasal wall were discretized with 0.6 mm triangular elements. Particularly, since maxillary ostia are quite small, the surfaces of the whole sinuses and ostia were refined with 0.3 mm triangular elements. Tetrahedral elements were then generated based upon these triangular elements. Besides, five prism layers were generated around the tetrahedrons to more accurately predict the near-wall viscous effect similar to our previous study

Table 2
Volumes of left and right nasal airways in pre- and post-operative models.

	Left Airway	Right Airway	Total
Volume of pre-operative model (ml)	17.07	9.73	26.80
Volume of post-operative model (ml)	13.70	16.74	30.44

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