Effects of Anterior Ethmoidectomy with and without Antrotomy and Uncinectomy on Nasal and Maxillary Sinus Airflows: a CFD Study

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Abstract

The effects of anterior ethmoidectomy, alone or combined with antrotomy and uncinectomy, on nasal and sinus airflow patterns were investigated using computational fluid dynamics (CFD) analysis of computed tomography scan-based three-dimensional nasal model reconstructions. The velocity, pressure, and airflow distribution, and airflow pathlines were evaluated. In model I, operated and non-operated airways were compared. In model II, the maxillary sinus was artificially sealed to evaluate the effects of ethmoidectomy alone. For both models, CFD simulations showed that post-op middle meatus airflow patterns were strongly affected, with higher air velocity, lower pressure, and larger-sized vortices, and the overall middle meatus airflow was redistributed laterally into the sinus cavities and away from the septum and superior meatus. Airflow rates at other intranasal sites were unaffected. The increase in post-op maxillary ventilation is larger than those in normal sinuses and sinuses with accessory ostia. Uncinectomy and antrotomy affect only local airflow within the antrum. In conclusion, middle meatus endoscopic sinus surgery (ESS) increases air exchange between sinuses and the nasal airway, increases middle meatus airflow at the expense of superior meatal flow, and produces vortices in the antrum and ethmoid. However, both ethmoidectomy and antrotomy/uncinectomy affect only local airflow, with negligible influence far from the operation site. These computed changes help us understand why dryness and mucus crusting is likely to occur after middle meatus ESS.

Keywords: Endoscopic sinus surgery (ESS), Ethmoidectomy, Uncinectomy, Antrotomy, Maxillary sinus, Computational fluid dynamics (CFD)

1. Introduction

Endoscopic sinus surgery (ESS), proposed by Messerklinger [1], has become the primary technique for treating sinonasal diseases such as mucocele, sinusitis, and nasal polyps. However, after decades of surgical operations, there are still lingering debates regarding the physiological effects of ESS. For example, the question of whether to preserve the middle turbinate is still controversial [2-4], and the question of whether it is better to preserve or enlarge the maxillary sinus ostium1remains unanswered [5]. In particular, although both antrotomy with uncinectomy and maxillary balloon catheter dilatation attempt to increase sinus ventilation by enlarging maxillary ostia, neither the effects of these two operations on sinonasal functions, nor the differences between them, are fully understood [6].

Airflow patterns in nasal cavities have been well reported [7-10], but sinus physiology and the effects of ESS interventions are still quite limited due to the poorly accessible location of the sinuses and the lack of noninvasive techniques for studying sinus physiology in living persons. For example, during ESS, uncinectomy is usually performed when the ostiomeatal complex is affected by disease, and anterior ethmoidectomy is frequently added to optimally decompress the ostiomeatal complex [11]. However, the effects of these combined operations on sinonasal functions, such as sinus ventilation, are not known. Since air flow, air filtration,
humidification, and olfaction are dependent on sinus and nasal cavity morphology, such data would be beneficial for better prediction of the outcomes of ESS operations, and the selection of the appropriate ESS techniques for a specific clinical condition. It has been reported that the sinus ventilation rate is increased by introducing an extra sinus ostium between sinus and nasal airways [12-14]. The effects of functional ESS, such as uncinectomy, natural ostia dilatation [6], and uncinectomy with middle meatal antrostomy [15], on airflow and particle deposition patterns have also been evaluated. The current study uses noninvasive high-resolution three-dimensional (3D) computer modeling to determine sinonasal airflows resulting from a common combination of ESS procedures, namely maxillary antrotomy with uncinectomy and anterior ethmoidectomy.

2. Materials and methods

A high-resolution computed tomography (CT) sinus scan of an 84-year-old Caucasian male with allergic rhinitis, completely healed after unilateral combined antrotomy, anterior ethmoidectomy, and uncinectomy for inverting papilloma, was used for 3D computational fluid dynamics (CFD) nasal model reconstructions. With a straight septum and similarly sized and shaped inferior and middle turbinates, his nose has excellent bilateral symmetry. The post-op left maxillary sinus (Fig. 1) is widely open and extensively connected to the left nasal airway and the left nasal airway is enlarged into the anterior ethmoid sinus, while the right nasal airway is normal.

![Figure 1. Coronal CT cross section at the operation site showing the outcome of left ethmoidectomy and uncinectomy.](image)

Commercial software MIMICS (Version 15.01, Materialise n.v., Leuven, Belgium) was used to construct the 3D model. CT pixels representing cavities were selected by the function thresholding, and then manual adjustment and refinement were done to improve the model morphology. Commercial software HYPERMESH (Version 11.0, Altair Engineering Inc., Troy, MI, USA) was used to discretize the 3D model into tetrahedral computational elements. Figure 2 shows the hemisphere, mathematically representing the surrounding atmospheric environment, which was created to enclose the nostrils. The complete 3D model consists of the face, nasal cavity, left and right sinuses, and the nasopharynx. By comparing airflow in the left nasal airway and sinus with that on the right side (model I), the effects of ESS on nasal and sinus airflow patterns were evaluated. An additional model (model II), with the antrotomy between the left maxillary sinus and the nasal airway virtually closed in the computational model, was created to evaluate the effects of ethmoidectomy without antrotomy and uncinectomy. Compared with nasal airflow, normal maxillary ventilation is negligible [14]. It can therefore be neglected during model II calculations. To simplify computations, the model resolution varied: the approximate size of elements around the hemisphere and face was 1.5 mm, that within the nasal cavity was about 0.6 mm, and that within the sinus walls was about 0.3 mm. In addition, as shown in Fig. 3, five prism layers, each layer 0.05 mm thick, were created to capture near-wall viscosity effects. Point P was defined to measure the variables at this point for the grid dependency test. Including all the prismatic layers and tetrahedrons, there were 5,126,783 and 4,085,135 3D elements created in models I and II, respectively. As shown in Fig. 4, the pressure and velocity magnitude at point P converged while the number of elements reached the current mesh resolution. Therefore, the current mesh resolution was utilized to maintain the accuracy of the simulation as well as reduce the computational burden of transient simulation.

![Figure 2. 3D models of the nasal cavity. Model I is the original model after the surgical interventions. Model II is the model with left maxillary sinus blocked. In both models, cross sections 1 to 12 were selected to investigate velocity magnitude distribution within the cavity.](image)

![Figure 3. Mesh of coronal cross section of model I. Point P was selected for grid dependency test.](image)
During simulation, air was assumed to be Newtonian and incompressible. Since the space between the sinus and the nasal airway is quite small and the sinus ventilation might be sensitive to the transient development of nasal airflow, transient simulation was carried out, instead of quasi-steady-state airflow simulation, in most of the reported airflow simulations. The mucus transportation speed is relatively low compared to nasal airflow rate, and thus the mucus layer was simplified as being part of the nasal wall. The nasal ventilation rate was assumed to be 10 L/min, with the instantaneous nasal airflow rate varying sinusoidally with time in a respiratory cycle that was 4 s long, with 2 s of inspiration followed by 2 s of expiration. Since the nasal airflow rate varies between zero and 31.42 L/min, Wilcox’s [16] low-Reynolds-number turbulent model was used to simulate laminar, transitional, and fully turbulent flow. Commercial software ANSYS FLUENT (Version 14.0.0, ANSYS, Inc., Canonsburg, PA, USA) was used to solve continuity, Navier-Stokes, and turbulent flow equations. This CFD method has been previously validated by comparing the numerical results with reported experimental data for other typical nasal airflows [17]. The PISO scheme was chosen for the pressure-velocity coupling in the equations. The second-order upwind scheme was used for the discretization of momentum and turbulent variables, and a standard interpolation scheme was used for pressure. These results were considered to be converged once the residuals of all the variables reached $10^{-4}$. At the maximum load of inspiration, the average and maximum Y+ values are 0.37 and 2.49, respectively. Therefore, the current boundary layer mesh setting is sufficiently fine to capture the near-wall viscosity effects of the airflow. For the transient simulation, the time step was set to be 0.05 s. The results obtained with time steps of 0.1 and 0.05 s had a small difference of less than 1%. Therefore, the current time step size is sufficiently short to capture the transient effect. For each of the models, two respiration cycles were simulated, and the results from the second cycle were used for analysis since they achieved periodicity.

3. Results

3.1 Antrotomy and uncineectomy plus anterior ethmoidectomy

Figure 5(a) shows model I frontal view cross sections between the nasal vestibule and the nasopharynx. Morphologically, within a given cross section, the two airways are quite comparable except for the operated site, which supports our assumption that the right nasal airway can be used as the benchmark for comparison. Around the nasal vestibule, the airflow is mainly concentrated near the medial nasal floor of cross section 1. Anterior to the middle turbinate, in the nasal valve area, the velocity distribution is quite comparable between the left and right airways (cross sections 2-4). However, in sections 5-7, the velocity magnitude around the middle meatus is quite different between the left and right airways. In the right middle meatus, the airflow is constrained by the middle turbinate and uncinate process, and the velocity magnitude is quite evenly distributed between these two structures. In the left meatus, as the nasal air space has been superiorly extended due to ethmoidectomy, and laterally enlarged due to uncineectomy, the velocity magnitude is much higher beside the middle turbinate and much lower laterally, close to the maxillary sinus. In addition, the velocity magnitude in the left middle meatus is increased, compared to that in the right meatus, and the velocity magnitude in the left middle meatus remains higher than that in the right middle meatus until section 10, close to the posterior-most nasal cavity. The airflow distribution becomes comparable between the two airways again in sections 11 and 12, at the posterior-most extent of the turbinates. The other easily observed difference is the much more extensive airflow visible inside the left sinuses, compared with the minimal flow within the right sinuses. Figure 5(b), model II, shows that except for flow within the antra, there is no significant difference in airflow patterns between the models.

Figure 6 shows an enlarged view of the velocity vector distribution from Fig. 5(a), cross section 6. In model I, for the left middle meatus, the airflow mainly passes through the medial side of the ethmoid air space in the lower half of the meatus, and through the lateral side in the upper half of the meatus. Two big vortices (indicated by grey arrows) formed beside the main flow stream in the lower and upper halves of the middle meatus. In the rest of the left and right airways, no other large vortices formed. In model II, findings were similar.
to those in model I, except for the formation of a more complex pattern of vortices in the ethmoid space.

Figure 6. Velocity vector distribution in cross section 6 in model I and model II at peak inspiration.

Figure 7 shows the percentage distribution of airflow over various sites. In the normal right airway, model I, the airflow percentages in the inferior meatus, middle meatus, and lower and upper common meatus are similar, with the lowest percentage of airflow seen in the middle meatus. In contrast, in the operated left airway, the highest percent of airflow was found in the middle meatus, due to the enlargement of that space. The airflows in the inferior meatus and lower common meatus are comparable and also similar to the corresponding parts of the right airway. Figure 7 also shows that the lowest airflow in any part of the nose was that in the post-op left upper common meatus, which had only 60% of the flow of the right side. This is reasonable, since the increased space in the post-op middle meatus could accommodate more airflow, while decreasing the amount of airflow passing through the upper common meatus. Surprisingly, the absence of an antrotomy/uncinectomy (model II) had negligible effects on flow distributions compared with the effects of anterior ethmoidectomy.

Figure 8 shows airflow pathlines through model I at peak inspiration. The airflow accelerated at the nasal valve region, decelerated in the middle of the nasal airway, and then accelerated again in the posterior nasal cavity before entering the nasopharynx. Despite surgery on the left, the flow pattern and distribution of velocity magnitudes is quite similar between the two airways. Maxillary and ethmoid pathlines are seen on the operative side, whereas none were found in the right sinuses.

Figure 8. Pathlines of the airflow in model I at peak inspiration.

Figure 9 shows the pressure distribution in cross section 6 at peak inspiration. Negative inspiratory pressure was greatest in magnitude inferiorly in both airways, and least superiorly. Interestingly, surgery produced increased negative pressure medial to the middle turbinate in the left upper common meatus. This lower pressure is caused by the acceleration of the upstream airflow around the middle meatus anterior to section 8 (as shown in Fig. 5). The pressure in the expanded left middle meatus is also lower, compared to that in the right middle meatus, due to the higher velocity magnitude in this region.

Figure 9. Pressure distribution in cross section 6 at peak inspiration.

Figure 10 shows the absolute airflow rate into the sinuses at a simulated ventilation rate of 10 L/min. The variation of sinus airflow with time is approximately sinusoidal in the post-op left side, and, as previously determined [14], negligible in the normal right sinuses. With a higher simulated ventilation rate of 15 L/min, an accessory maxillary ostium produced maximum sinus airflows of only 8 mL/s [14], compared to 26 mL/s after antrotomy, uncinectomy, and anterior ethmoidectomy.

A quasi-steady-state assumption was made in previous simulations, which is acceptable for nasal airflow patterns with low Wormersley or Strouhal numbers that describe flow during normal respiration. However, this assumption may not be valid when air exchange into sinuses is significant. As shown in
3.2 Anterior ethmoidectomy

The airflow effects of anterior ethmoidectomy alone, without antrotomy and uncinctomy, were also investigated. Surgical exposure of the antrum was undone in the computational model by omitting the left maxillary sinus from model I to create model II. It is known that flow through the natural ostium is quite small, and prior simulations have shown that sealing off the antrum produces useful comparisons [14].

With or without the left maxillary sinus, the velocity magnitude distribution is almost the same throughout the whole nasal cavity (Fig. 5), except for the operated site (indicated by arrows). In model I, two big vortices were produced beside the left middle meatus mainstream, whereas in model II, more, smaller vortices were produced (Fig. 6). The closure of the left sinus did not change airflow on the right side at all (Fig. 7); however, on the left side, the airflow in model II slightly decreased in all areas. The largest difference, a 15% drop, was found for airflow through the left middle meatus, adjacent to the operation site. The pressure contours also were similar; only a small change was found beside the left sinus (Fig. 9).

4. Discussion

In model I, anterior ethmoidectomy with antrotomy and uncinctomy mainly influenced velocity magnitude distribution (Fig. 5) and pressure distribution (Fig. 9) in the left middle meatus, while airflow far from the operative site was minimally affected. Though the whole air space has been opened up around the left maxillary sinus ostium, the main airstream still flows closely by the lateral surface of the middle turbinate. This is caused by airflow patterns from the upstream (anterior), constrained by the nasal valve, which directs the airflow laterally, toward the turbinates and sinus ostia. Surgery repartitioned the airflow through the left middle meatus and left common meatus. As the air space enlarged, airflow rates through the left middle meatus increased at the expense of airflow through the left upper common meatus. However, surgery mainly affects local airflow distribution, since the airflows at other sites are similar between left and right airways.

One interesting feature of post-op local airflow is that the main airstream did not flow by the lateral middle turbinate all the way up to the ethmoidal roof. Instead, the high velocity airstream deviates laterally to contact the superior lateral side of the ethmoidal sinus (Fig. 6). This curved high-velocity airstream inside the ethmoid might be caused by recirculation. In addition, the increased space in the post-op middle meatus makes this region prone to the occurrence of flow vortices. For example, besides the large vortex in the antrum, two medium-sized vortices were found beside the main ethmoid airstream. The observed vortices might explain the occurrence of dryness and crusting, which may occur following middle meatal ESS.

Antrotomy and uncinctomy caused increased air exchange between the antrum and the nasal airway compared to airflow into sinuses with accessory ostia, and much more airflow than is seen in maxillary sinuses with healthy, natural ostia [14]. The airflow distribution in antra also differs with the kind of ostium. With normal ostia, there is no high velocity airflow, whereas with accessory ostia, high-velocity airflow mainly appears between, or in line with the ostia. In the current antrotomy/uncinctomy model, high-velocity airflow mainly appears near the sinus walls, with a lower velocity magnitude in the center of the antrum. The observed airflow differences are caused by the intrinsic characteristics of the aerodynamics of these sinuses. In a normal antrum, airflow is driven mainly by the shear forces at the ostium, and no significant flow is observed due to the extremely small size of the ostium. With accessory ostia, airflow is mainly driven by the pressure difference between the ostia, and thus a high velocity magnitude appears between the ostia. After uncinctomy, the enlargement of the maxillary ostium increased the influence of the shear force from the airflow passing through the middle meatus as well as the pressure difference alongside the enlarged ostium on the airflow in the maxillary sinus, resulting in high flow rates close to the wall. This data suggests that uncinctomy should be more effective in improving sinus ventilation compared to middle meatus antrotomy.

A comparison of model I with model II indicates that
uncinectomy and antrotomy influenced only local nasal airflow. Uncinectomy/antrotomy induced a lower velocity magnitude near the lateral wall of the middle meatus (Fig. 5), fewer large vortices (Fig. 6), slightly higher airflow through the left middle meatus (Fig. 7), and slightly lower pressure around the middle meatus lateral wall (Fig. 9).

There are a few limitations to using this CFD model. Firstly, the right nasal airway was used as the comparator for the left. Ideally, there should be a pre-op CT as the control. However, since our results show that these ESS operations affected the airflow patterns only locally, this assumption was found to be acceptable. Secondly, model II was used to simulate airflow patterns in a nasal cavity that had undergone only ethmoidectomy; however, the air space in the left middle meatus is also enlarged by uncinectomy. In addition, since the surgical interventions are not reversible, this model cannot be used to investigate the effects of uncinectomy alone on nasal airflow.

5. Conclusion

In conclusion, 3D CFD modeling of the effects of anterior ethmoidectomy, antrotomy, and uncinectomy shows increased air exchange between sinus and nasal airways and increased middle meatus airflow. Vortices were produced in the antrum and ethmoid due to the volume increase, which may explain the potential for post-op drying and crusting. These ESS interventions affect airflow patterns only locally, with airflow far from the operation site minimally affected, and do not affect contralateral airflow at all. Ethmoidectomy, without antrotomy and uncinectomy/antrotomy only slightly influenced nasal airflow distribution in the left middle meatus. Uncinectomy significantly increases maxillary ventilation compared to sinuses with normal or accessory ostia.

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References