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Sinus irrigations before and after surgery – visualization through computational fluid dynamics simulations

Kai Zhao, Ph.D.^{1,2}, John R. Craig, M.D.³, Noam A. Cohen, M.D., Ph.D.^{1,3,4}, Nithin D. Adappa, M.D.³, Sammy Khalili, M.D.³, and James N. Palmer, M.D.³

¹Monell Chemical Senses Center, 3500 Market ST, Philadelphia, PA 19104

²Department of Otolaryngology-Head & Neck Surgery, Thomas Jefferson University, 925 Chestnut Street, Sixth Floor, Philadelphia, PA 19107

³Department of Otorhinolaryngology, University of Pennsylvania, 5 Ravdin, 3400 Spruce Street, Philadelphia, PA 19104

⁴Philadelphia Veterans Affairs Medical Center, 3900 Woodland Ave, Philadelphia PA 19104

Abstract

Objective—Topical sinus irrigations play a critical role in the management of sinonasal disease, and the improvement in irrigant penetration into the sinuses postoperatively greatly contributes to the success of the endoscopic sinus surgery. Prior investigations on postoperative sinus irrigations have been mostly limited to cadaver studies, which are labor intensive, and do not capture the full dynamics of the flows. A pilot study was conducted to investigate the impact of surgery on sinus irrigation through Computational Fluid Dynamics (CFD) simulations.

Study Design—Retrospective computational study

Methods—Pre- and postoperative CT scans were obtained on a patient who underwent standard Endoscopic surgeries for all sinuses, including a Draf III frontal sinusotomy. CT based pre- and postoperative CFD models then simulated irrigations of 120 mL saline per nostril at 12mL/s (typical of Sinugator[®]) and 60mL/s (SinusRinse Bottle[®]), in two head positions: face parallel and at 45° angle to the ground.

Results—Overall, surgery most significantly improved frontal sinus irrigation, but surprisingly resulted in less maxillary and ethmoid sinuses penetration. This may due to the partial removal of septum during the Draf III, causing most fluid to exit pre-maturely across the resected septum. Higher flow rate slightly improved ethmoid sinus irrigation, but resulted in less contralateral maxillary sinus penetration.

Co-Corresponding authors:

Kai Zhao, Monell Chemical Senses Center, 3500 Market ST, Philadelphia, PA 19104, kzhao@monell.org, 267-519-4935
James N. Palmer, Department of Otorhinolaryngology, University of Pennsylvania, 5 Ravdin, 3400 Spruce Street, Philadelphia, PA 19104, James.Palmer@uphs.upenn.edu

This manuscript contains 6 supporting videos to illustrate our key findings.

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Conclusions—CFD modeling of sinonasal irrigations is a novel technique for evaluating irrigant penetration of individual sinus cavities. It may prove useful in determining the optimal degree of surgery or the ideal irrigation strategy to allow for maximal and targeted sinus irrigant penetration.

Keywords

Nasal irrigation; Computational Fluid Dynamics; Modeling; sinus surgery; sinusitis; frontal; maxillary; sphenoid; head position

Introduction

Topical therapies play an integral role in the management of sinonasal disease, and high volume irrigation delivery is more effective for achieving distribution to the sinuses than other topical delivery methods such as nasal sprays, nebulizers, or atomizers.^{1–4} Saline irrigations have been recommended in a number of clinical scenarios, including chronic rhinosinusitis⁵ and postoperative care⁶. High volume irrigations have also shown benefits for medication delivery, such as with mupirocin⁷ and budesonide^{8;9}. The improvement of sinus irrigation penetration thus increasingly becomes an important outcome of endoscopic sinus surgery. In efforts to improve these outcomes, the efficacy of topical irrigations delivery to target sinuses is an area of active research. Previous studies have shown that nasal irrigant may not reliably penetrate all sinuses¹⁰ and its effectiveness in postoperative cases varies,³ and may depend on the degree of surgery, e.g. ostia size.¹⁰ The head position during the irrigation may be another important factor, but its impact may differentially depend on specific sinuses, as well as the delivery device volume and pressure.¹¹

The investigations into determining distribution of sinus irrigations have been limited by labor-intensive methodologies. Blue-dyed irrigations have been applied to live patient and cadavers, followed by endoscopy to visualize where the irrigation might have reached^{10;11}. Other studies have used irrigations with iodinated contrast followed by computed tomography (CT) scans to determine which sinuses collect contrast material^{3;12}. Similarly, Technetium 99m sulfur colloid¹ and fluorescein¹³ labeled irrigations have also been used as tracers to visualize the distribution of sinus irrigations. In addition to being labor-intensive, these methods commonly only capture where the irrigation fluid has been at the end of irrigation.

To better understand and predict where topical irrigations travel within the sinonasal cavities, the complete flow path of the irrigations as they were pushed from the tip of the irrigation delivery device and drained throughout all the sinonasal cavities would be necessary. The purpose of this study was to apply a computation fluid dynamics (CFD)¹⁴ simulation technique to pre- and postoperative sinonasal cavities to visualize the dynamic flow of sinus irrigations. CFD technique has been widely utilized in the past in field of Rhinology to simulate nasal airflow^{15–17}, heat exchange¹⁸, aerosols¹⁹ and volatile chemical dispersion^{20–22}, and this study represent the first attempt to extend CFD technique to the investigation of nasal irrigation.

Method

Preoperative and postoperative CFD models of sinus irrigations were created based upon preoperative and postoperative computed tomography (CT) maxillofacial scans from a 47 year-old male patient with chronic rhinosinusitis who had undergone revision endoscopic sinus surgery of all eight sinuses. The surgery included bilateral wide maxillary antrostomies, total ethmoidectomies, sphenoidotomies, and a Draf III frontal sinusotomy. The Draf III procedure included resection of the anterosuperior portion of the middle turbinates, a superior nasal septectomy, and drilling out of the nasofrontal beak and frontal intersinus septum.

The preoperative and postoperative CFD models were created according to previously published methods.^{23;24} In brief, first the interface between the nasal mucosa and the air was delineated on the CT scans using AMIRA® software (Visualization Sciences Group, Burlington, MA) (see Figure 1). Then, the nasal cavity air space was filled with tetrahedral elements using ICEMCFD® software (Ansys, Inc., Canonsburg, PA). After refinement and correction for errors, the final models contained 2.3 and 3.2 million elements for pre- and postoperative models, respectively.

Pre- and postoperative irrigations of 120 mL saline per nostril were then simulated at two speeds: 12mL/s for 10s (typical of Sinugator®, NeilMed) and 60mL/s for 2s (typical of SinusRinse Bottle®, NeilMed). These volume and flow rate values were obtained by authors performing these irrigations on themselves and recording the volume and speed repetitively. Simulated irrigations were performed in two head positions: face oriented parallel to the ground (referred to as 90° head position), and face oriented at 45° from the ground (see top left insert in Figure 2 and 5). For boundary conditions, a circular opening of 4 mm in diameter was created at one of the nostril planes to represent the irrigation bottle opening, where the saline solution would be forced into the nasal cavity at the designated flow rates. The contralateral nostril was set as a mass outlet (the only outlet), through which air and saline could exit. The nasopharyngeal opening was assumed to be blocked off by the soft palate and impenetrable to liquid or air. The nasal mucosal wall was assumed to be immobile and smooth. The simulations were carried out by a commercial CFD software, CFX® (Ansys, Inc., Canonsburg, PA), using the multiphase free surface method. “Coupled volume fraction” and “Density difference (buoyancy)” were selected in the multiphase model with fluid surface tension set at 71 dyne/cm and earth gravity set at 9.8m/s². The multiphase model serves to define the interaction between different fluid phases: air and saline solution in our case. Air, much less in density, would rise and remain atop of the saline solution, as defined by the gravity force and density difference. A k-ε turbulence model was utilized to simulate details of both air, and saline fluid movement as well as accounting for the initial saline fluid momentum exerted by the irrigation bottle. The advection scheme and turbulence Numerics were both set at “high resolution”. The simulation applied a transient scheme with second order backward Euler to capture the full fluid motion during the irrigation, with an initial time step set at 5e⁻⁶s and the adaptive time steps set based on the target optimal number of iteration loops (3–5), and minimum and maximum time step (1e⁻⁶s – 0.01s). Convergency criteria were set at root mean square (RMS) of the residue < 1e⁻⁴.

The model creation takes about 1 day to complete, but one simulation of irrigation takes ~7 days to complete on a dell Precision T7400 workstation with dual quad-core Intel Xeon X5472 CPUs in parallel mode. A total of 16 simulations (combinations of pre- and postoperative, 2 flow rates, 2 head positions, and irrigation from left vs right nostril) were completed. Video files and still images were created for each simulation.

Results

Pre- and postoperative CFD simulated nasal irrigation into the left nostril at 90° head position are shown for flow rates of 12 mL/s (Figure 2) and 60 mL/s (Figure 3). Figure 4 shows an example of time sequence snapshots: irrigation fluid would first fill the ipsilateral side ($t=0.03-1$ s), irrigating the maxillary and ethmoid sinuses ($t=0.25-5$ s), and then overflow and spill over the posterior end of the septum to irrigate the contralateral side ($t=2.5-5$), before draining out of the contralateral nostril. Due to space limitation, only the end-of-irrigation snapshots are presented in other figures, however, please see supporting Videos 1–6 for full dynamics of irrigation fluid movement.

Preoperatively, the frontal sinuses were not penetrated by any irrigations. Ipsilateral maxillary and ethmoid sinuses were relatively well irrigated (filled with irrigation fluid in blue pseudo-color). Higher flow rate (60 mL/s) resulted in more violent fluid splashing (seen in Videos 3) and slightly enhanced ethmoid sinus irrigation, but resulted in less penetration of the contralateral maxillary sinus preoperatively than the slow (12 mL/s) flow rate.

Postoperatively, after the Draf III, irrigation flow dynamics changed drastically. For both flow rates (Figure 2 and 3), irrigations penetrated well into the frontal sinuses as expected. However, irrigations were limited in the anterior sinonasal cavities, and did not rise posteriorly into the maxillary and other sinuses, which may be due to the partial removal of superior septum and frontal intersinus septum during the Draf III, causing irrigation fluid to spill pre-maturely across the opened septums (Figure 1).

45° head position resulted in differential irrigation results: less maxillary and ethmoid sinuses penetration preoperatively (see Figure 5), but more maxillary sinus penetration post surgery compared to the 90° head position; while the frontal sinus penetration status remain the same. Sphenoid sinus was not well penetrated by irrigant in all cases. Irrigations from the right nostril resulted in very similar irrigation patterns than from the left nostril (see examples in Figure 6).

Discussion

Studying the distribution of topical irrigations to the sinus cavities has been challenging. A few studies have evaluated irrigation distribution in either cadavers or live patients, using various tracers, e.g. colored dye, iodinated contrast, and fluorescein label^{1,3;10-13}, however, only focused on the final distribution and residual, rather than the dynamics of irrigation flow. These studies are labor intensive to perform, but have demonstrated that irrigations don't consistently reach all regions within the nasal or sinus cavities before or after sinus surgery, and it remains challenging to predict the exact degree of irrigation penetration.

The CFD model presented in this study provides a number of benefits over previously used methods to evaluate distribution of sinonasal irrigations. One significant advantage of the CFD model is that it can predict not only the final destination of irrigations, but also demonstrates the dynamic flow of irrigations as they traverse the sinonasal cavities. This provides a more accurate depiction and understanding of topical irrigation distribution, rather than evaluating whether irrigation penetrates a given sinus as an all-or-none phenomenon. Another advantage over other techniques is that it causes no discomfort to the patients. One of the key findings of this study is the impact of removal of superior and intersinus septums during the Draf III that unexpectedly caused irrigation fluid to spill prematurely across the resected septum and reduced the irrigation to other sinuses. Septum preserving surgical options (e.g. Draf II) may potentially prevent such adverse outcome, pending future studies with more cases and more validations.

Other findings of the study have generally good agreement with previous irrigation tracing studies. For example, Grobler et al¹⁰ suggested that ostial opening size may be an important limiting factors in maxillary sinus irrigation, which we agree upon in our data by showing that low flow rate (12 mL/s) resulted in more penetration of the contralateral maxillary sinus than the high (60 mL/s) flow rate preoperatively. This counter-intuitive outcome can be explained by the fact that the preoperative maxillary ostium diameter in our model is measured at 2.9 mm, towards the narrow end of spectrum¹⁰, thus it takes time for fluid to drain into the maxillary sinus (see snapshots from t=1s to t=5s in Figure 4). As the result, slower but longer irrigation (given a fixed irrigation fluid volume) may be helpful for irrigating through narrow maxillary ostium by allowing more time for the irrigation fluid to pool and drain through the ostial opening. Postoperative, the ostium size increased to 12.9mm, which should be large enough not to impede any fluid penetration. But as we discussed above, the removal of superior and intersinus septums in Draf III had the adverse effect that prevented the irrigation fluid from reaching the maxillary ostium, thus the maxillary irrigations were significantly reduced. This outcome demonstrated the challenge of predicting nasal irrigation dynamics based on physical parameters alone.

Harvey et al³ reported that the frontal sinus irrigation improved greatest postoperatively, and Singhal et al¹¹ reported that frontal sinus irrigation remain similar between the head position of 45° and 90° (they called it 0°), which both match our results. The 45° head position results also demonstrated the complexity in predicting irrigation outcome: compared to 90° position, less maxillary and ethmoid sinus penetration preoperatively, but more maxillary sinus penetration postoperatively (see Figure 5). This can be explained by the spatial orientation between the spill-over locations and the sinuses. For the preoperatively case, 45° position would tilt the nasopharynx lower than ethmoid and part of the maxillary sinuses compared to 90° position, thus preventing fluid rising to these locations. But for the postoperative case, 45° position would tilt the resected septum higher than part of maxillary sinus, thus improving maxillary penetration prior to fluid spilling over the resected septum. On the other hand, as frontal sinuses consistently remain below the spill-over locations in either head positions, its irrigation outcome remains unaffected.

Obviously, there are still discrepancies between our results and the literature, especially regarding the sphenoid sinuses, which could be due to anatomical differences between the

subjects or irrigation techniques. On the other hand, CT-based CFD model needs also to be further validated. One way to do this is by comparing results from the CFD model to results from video-endoscopy of cadavers before and after sinus surgery, utilizing CT scans before and after surgery to create the CFD model for each respective cadaver. We are also currently conducting this project. The long computational simulation time may represent another limitation of its potential clinical application, but with future faster and cheaper computer hardware and easily scale-up parallel processing on clusters with more CPUs, this limitation can be potentially overcome in the future.

Conclusion

CFD modeling of sinonasal irrigations is an intriguing technique for evaluating irrigant penetration of the entire sinonasal cavity. It may prove useful in predicting the optimal degree of surgery or ideal head positioning post-op to allow for maximal or directed sinus irrigant penetration.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Preoperative

Postoperative (Draf III)

Figure 1.

Pre and postoperative CT scans of the patient. The interface between the nasal mucosa and the air was delineated using AMIRA® (shown in red) so that sinonasal cavity models can be computationally created subsequently. Preoperatively, frontal sinuses were completely blocked off from the main nasal airway (red indicating air space connected to the outside). The removal of superior septum during the Draf III may cause irrigation fluid to cross prematurely across the superior septum (green arrow).

Figure 2.

CFD simulated nasal irrigation into the left nostril, at 90° head bent position at 12 mL/s flow rates both pre- (top row) and postoperatively (bottom row), snapshots at the end of irrigation ($t=10s$). Color code is saline fluid velocity (0–2 m/s), which apply to all subsequent figures. Frontal sinuses were not penetrated preoperatively, but fully irrigated postoperatively. The ipsilateral maxillary and ethmoid sinuses were well-irrigated preoperatively. After the Draf III, the removal of superior septum may cause irrigation fluid to spill pre-maturely across the superior septum, and therefore decrease maxillary and ethmoid sinuses penetration.

Figure 3. CFD simulated nasal irrigation into the left nostril, at 90° head position at 60 mL/s flow rates both pre- (top row) and postoperatively (bottom row), snapshots at the end of irrigation (t=2s).

Figure 4.

Snapshots at $t=0.03$, 0.3, 1, 2.5, 3.5, 5s of CFD simulated preoperative nasal irrigation to the left nostril, at 90° head position at 12 mL/s flow rates. End of irrigation snapshot ($t=10$ s) can be found in Figure 2 (top row). Irrigation fluid would first rise up in the ipsilateral side ($t=0.03$ –1s), irrigate the maxillary and ethmoid sinus ($t=2.5$ –5s), and then overflow and spill over the posterior end of the septum to irrigate the contralateral side ($t=2.5$ –5s), before draining out of the contralateral nostril.

Figure 5.

CFD simulated nasal irrigation into the left nostril, at 45° head position at 12 mL/s flow rates both pre- (top row) and postoperatively (bottom row), snapshots at the end of irrigation (t=10s).

Figure 6.

CFD simulated preoperatively nasal irrigation into the **right** nostril, at 90° head position at 12 mL/s (top row) and 60 mL/s (bottom row) flow rates, snapshots at the end of irrigation.