Characterization of nasal irrigation flow from a squeeze bottle using computational fluid dynamics

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Background: Nasal saline irrigation has become standard of care in various sinonasal conditions, including allergic and nonallergic rhinitis, chronic rhinosinusitis, and in the postoperative patient. Evidence regarding the mechanisms and dynamics of liquid flow through the sinonasal cavity remains limited due to inadequate experimental models (cadaveric, 3-dimensional [3D] printed, imaging of labeled dyes and radioisotopes). We aimed to develop a computational fluid dynamics (CFD) model of nasal irrigation to demonstrate sinonasal surface coverage, residence times across the mucosal surfaces, and shearing force of irrigation.

Methods: A nasal cavity geometry derived from high-resolution paranasal sinus computed tomography (CT) scans of a healthy, unoperated, 25-year-old patient was created. CFD analysis was performed to assess the distribution of nasal irrigation from a tapered nozzle bottle at a forward head-tilt position of 45 degrees with a 2-second burst at 35 mL/second.

Results: The model demonstrates nasal irrigation from ipsilateral to contralateral with precise measures of velocity, pressure, wall shear stress, and mapping of surface coverage and residence times at specific locations and times. The nasal cavity experiences almost complete coverage of irrigation, while overflow from the nasal cavity facilitates moderate coverage of the ipsilateral maxillary (40%) and anterior ethmoid sinuses (30%). Negligible coverage of the sphenoid and frontal sinuses was noted.

Conclusion: Detailed physical mechanisms of liquid irrigation injected from a commonly used squeeze bottle were shown. Ipsilateral maxillary and ethmoid sinus penetration are primarily due to overflow rather than direct jet entry, confirming the recommendation of larger volumes of irrigation to “flood” the sinus ostia. © 2019 ARS-AAOA, LLC.

Key Words: nasal airflow dynamics; computational fluid dynamics; computer modeling of airflow; irrigations; CFD

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Saline irrigation has been recommended in international consensus statements for the treatment of various sinonasal conditions, including allergic and nonallergic rhinitis,¹ acute and chronic rhinosinusitis (CRS),²,³ and for patients undergoing sinonasal surgery, both in the early and long-term postoperative period.² It has also been demonstrated to be beneficial in lavaging the mucosal surface of inflammatory products and hypersecretory mucin, as well as delivering topical medications to diseased mucosal tissue. Although the benefits of nasal irrigation are well established,⁴ ⁵ the mechanisms and dynamics of liquid flow through the sinonasal cavity remain poorly understood. In particular, detailed information regarding liquid velocity, pressure, and volume at various locations and at different time points in the irrigation process is critical to understanding current mechanisms and developing improved techniques.⁶
The creation of accurate models of irrigation flow, with measurable results, permits the testing of various parameters, including patient factors (head position, squeeze pressure), anatomical factors (presence of septal deviation, turbinate hypertrophy), surgical factors (extent of sinus surgery), and device factors (squeeze bottle vs gravity-feed, nozzle size, angle, position).

Existing experimental evidence has been largely derived from cadaveric or 3-dimensional (3D) printed models, assessed with nasendoscopes. Such models are limited by their capacity to only examine individual sinuses, the reliance on subjective human interpretation without precise, quantifiable data, and the inability of cadaver specimens to accurately reflect the physiological conditions of the live patient.

Other attempted models have used contrast-enhancing dyes or radioisotopes followed by computed tomography (CT) or scintigraphic imaging, respectively. Such models have demonstrated data on sinus distribution of liquids but are only able to assess residual volumes and are unable to provide real-time information on the how the irrigation flow interacts with sinonasal anatomy during the irrigation process.

To date, limited evidence from such models has shown that patient head position, the extent of surgical access, and the type of nasal irrigation device have been demonstrated to affect irrigation penetration, distribution, and force within various paranasal sinuses. As a result, the use of nasal irrigation with a squeeze bottle was recommended in international consensus statements for the treatment of CRS. Cadaveric studies have demonstrated that only around 2.5% of irrigation fluid is retained in the nasal cavity or paranasal sinuses, with the highest residual volume in post-endoscopic sinus surgery (ESS) patients followed by non-operated controls and patients with CRS.

Computational fluid dynamics (CFD) represents a novel, validated method of modeling air and fluid flows through the sinonasal tract that is highly accurate, quantifiable, reproducible, and allows multiple permutations to be rapidly assessed to determine the ideal combination of parameters. Despite this, only a few CFD studies of nasal irrigation have been performed. These include Zhao et al. and Craig et al., who explored squeeze-bottle nasal irrigation and found the nose-to-ceiling head position was superior to the nose-to-floor position for irrigation to the sphenoid sinuses; and Salati, who investigated gravity-fed nasal irrigation (using neti pots) and found that maximum saline distribution in the nasal cavity was observed in the Mygind head position.

This study aimed to characterize nasal irrigation by identifying the critical fluid dynamics mechanisms that dominate the jet stream flowing through a human sinonasal cavity. It is expected that these key flow behaviors would persist despite different patients and different parameters. New, and highly quantitative analysis techniques were developed for determining sinonasal surface coverage of nasal irrigation, residence times across the mucosal surfaces, and shearing force of irrigation. It is expected that the visual results and quantitative analysis could lead to potential device modifications to improve both topicalization of medications and irrigation force for lavage.

Materials and methods

Nasal cavity model

A realistic nasal cavity geometry was reconstructed from a high-resolution CT scan of a healthy 25-year-old, Asian female (161 cm height, 53 kg mass, without nasal septum deviation, turbinate hypertrophy, or sinusitis) at resting conditions. The CT data was acquired using a Dual Source CT scanner with image parameters of 0.39 × 0.39 mm pixel size, 512 × 512 pixels image dimensions, and 0.5 mm slice thickness. The nasal cavity and the entire paranasal sinuses including the maxillary, ethmoid, frontal, and sphenoid sinuses were extracted using 3D-Slicer’s segmentation tool by a computer engineer in conjunction with an ear, nose, and throat (ENT) surgeon. The geometry of the face was retained, and a hemisphere with a diameter of 200 mm was attached in front of the face. The soft palate was artificially “closed” in the computational model by creating a boundary wall surface. The sinonasal cavity model underwent mesh independence and mesh quality tests reported in Zhang et al. The final model contained 1.1 million polygonal cells (equivalent to 4.6 million tetrahedral cells) with 5 prism layers (first layer height of 0.07 mm, and total height of prism layer of 0.64 mm) using ANSYS-Fluent v19.2 meshing. The surrounding hemisphere was set as a pressure-outlet condition (Fig. 1A), and the entire domain was initially set as air with zero velocity. The liquid jet was introduced as a mass flow inlet at the squeeze-bottle nozzle which had a 5-mm diameter. All other surfaces were set to a wall boundary condition. Figure 1B shows the nasal geometry with a squeeze bottle (featuring a tapered nozzle) inserted into the left nostril until the nozzle occluded the nostril opening. The nozzle insertion distance (from the nozzle tip to the nostril) was 10 mm.

Jet flow stream (volume of fluid modeling)

In general, the practical consensus on administration technique is a 45-degree forward head tilt, although there is no evidence-based recommendation for this approach. Salati evaluated 4 different head positions for a gravity-fed neti pot nasal irrigation. These were supine (lying with head back), 90 degrees (tilting the head sideways at 90 degrees), head back (head oriented 45 degrees upward from the ground), and head forward (head inclined downward at 45 degrees to the ground). Instructions that accompany the Flo® sinus rinse bottle (ENT Technologies, Hawthorn East, VIC, Australia) suggest the head be angled forward at 45 degrees (head over sink). In our model, a head tilt position of 45 degrees forward was used, with the nozzle jet aligned vertically.
CFD of nasal irrigation

The nozzle jet diameter was 5 mm based on a commercially available nasal irrigation bottle (Flo®; ENT Technologies). The liquid jet was introduced into the airway from zero to a flow rate of 35 mL/second (approximately 1.79 m/second) held for 2 seconds. This gave a total volume of 70 mL based on preliminary testing of short physical squeezes of the current 200-mL Flo® bottle, where less than one-half the volume was ejected/used. The squeeze duration represented a rapid squeeze with the hand. The initial ramp-up and ramp-down times were both set at 0.01 seconds, selected to preclude ramp periods as a physical test variable. Future experiments will include sinusoidal ramp profiles of longer duration, which are more likely to accurately reflect physical conditions.

**Computational model setup**

The Eulerian volume of fluid model was used to track the interface between the liquid jet and the air described by the mass, and momentum conservation equations. The implicit body force option was applied to consider the partial equilibrium of the pressure gradient and the body forces. The Green-Gauss node-based method was used to calculate gradients at cell centers from face gradients and the PRESTO! scheme was used for pressure interpolation. The Second Order scheme was used for discretization of the momentum and turbulence equations. A second-order implicit scheme was used for the temporal discretization of the transient term. A variable time step (Δt), based on a fixed Courant number of 1, was used.

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**FIGURE 1.** (A) The complete computational domain labeled by the boundary conditions. (B) Lateral view (left chamber side) of the nasal cavity with irrigation bottle inserted into the left chamber. The paranasal sinuses are colored as: yellow (maxillary sinus), blue (sphenoid sinus), red (ethmoid sinuses), and green (frontal sinuses). (C) Coronal slice at x3 showing the left chamber only, depicting the poly-hexcore internal computational mesh. (D) Forward head tilt showing a 45-degree angle and the direction of the liquid jet (denoted by dashed blue arrow), which is vertically aligned, and (E) the jet profile set to a quasi-constant flow without the effects of ramping up/down durations. Please refer to supplementary video animation demonstrating the nasal irrigation setup.
Results
A video of key moments of the irrigation simulation can be found online (Supporting Video 1).

Early stages of nasal irrigation (t = 0 to t = 0.1 seconds)
The jet flow entering the nasal cavity in the early stages is shown in Figure 2, with front (anteroposterior) and lateral views. The images are shown with transparent nasal walls, and the liquid (water) is colored in blue. The jet immediately impacts onto the nearby lateral vestibule wall and the nasal septum (t = 0.012 seconds, t = 0.024 seconds) and quickly fills the anterior nasal cavity. Due to the head tilt, the initial jet flow also enters the anterior ethmoid sinus.

Nasal irrigation (t = 0.50 to t = 2.50 seconds)
After the initial jet injection, the left main nasal passage between the septum wall and turbinates is now covered by the liquid (Fig. 3). The nasopharynx is partially covered by the liquid, as the liquid turns and moves into the contralateral right nasal cavity, under the influence of gravity. The front view and right chamber views (Fig 3B, C) show the liquid moving along the floor of the right nasal cavity and exiting the right nostril after t = 0.5 seconds without ever reaching...
the right frontal, ethmoid, or sphenoid sinuses. Flow entering the right maxillary sinus was caused by liquid overflowing from the main passage. At the end of the nasal irrigation squeeze \((t = 2.0 \text{ seconds})\), the injection momentum ceases, and the liquid decelerates to a rest state and remains in the nasal cavity as a pool under the influence of gravity.

**Water volume fraction and velocity magnitude contours on coronal slices**

Instantaneous contours of water volume fraction (liquid/air mixture) and velocity are shown in Figure 4, which shows (in more precise detail) the left main nasal passage filling, leading to liquid flowing into the maxillary and ethmoid sinuses. Slice “x4” at the nasopharynx shows the liquid sloshing as it impinges on the posterior nasopharynx wall. The liquid returns through the right nasal cavity, where much of the liquid momentum has dissipated, and remains along the floor. At the end of the simulation at \(t = 3.0 \text{ seconds}\), there is still a significant amount of fluid remaining in the left cavity, including the anterior ethmoid and maxillary sinuses. The velocity contours show regions of high motion, which would correlate to higher wall shear stress (WSS). While the left nasal cavity fills with the liquid in its inferior half, the velocity (which represents the jet flow direction) is primarily in the superior half, suggesting the jet impinges on the superior walls, and settles to the inferior half, filling up the region. In the right chamber, both velocity and water volume fraction contours coincide.
Instantaneous water volume fraction contours

FIGURE 4. Coronal slices taken at locations x1, x2, x3, x4 (depicted in Fig. 1) showing the water volume fraction at (A) $t = 1.0 \text{ sec}$, (B) $t = 2.0 \text{ sec}$, and (C) $t = 3.0 \text{ sec}$, and velocity magnitude contours at (D) $t = 1.0 \text{ sec}$, (E) $t = 2.0 \text{ sec}$, and (F) $t = 3.0 \text{ sec}$. *The maximum velocity magnitude was 2.9 m/second but the contour legend was capped at 1 m/second to provide clearer visualization.
FIGURE 5. Transverse (axial) slices at y1, y2, y3, y4 (depicted in Fig. 1) showing the water volume fraction at (A) t = 1.0 seconds, (B) t = 2.0 seconds, (C) t = 3.0 seconds, and velocity magnitude contours at (E) t = 1.0 second, (F) t = 2.0 seconds, and (G) t = 3.0 seconds. *The maximum velocity magnitude was 2.9 m/second but the contour legend was capped at 1 m/second to provide clearer visualization.
Water volume fraction and velocity magnitude contours on transverse slices

Instantaneous contours of water volume fraction and velocity are shown in Figure 5, where slices y1 to y4 are in the superior-inferior direction of the transverse (axial) slices. The images show the influence of the 45-degree forward head tilt where the liquid overfill that enters the sinus fills up the anterior regions of the sinuses (y1, y3, and y4 in Fig 5A, back), and nasopharynx, whereas there are voids in their respective posterior regions. Surface coverage in the right nasal cavity is higher at the lateral nasal wall and less on the nasal septum. At the end of the simulation, the left nasal cavity contains residual liquid that is prevented from exiting by the occluded left nostril (from the nozzle device), while in the right cavity the liquid continues to exit the right nostril by gravity. The velocity magnitude contours show the high jet flow velocities in the superior slices of the left cavity (slice y2), while the right cavity has higher velocities in the inferior slice (slice y4).

Mapping the water coverage on nasal surfaces

The 3D nasal cavity walls were projected as 2-dimensional (2D) unwrapped surfaces (using the technique developed in earlier work) shown in Figure 6A. The nasal cavity was separated into a single continuous surface, whereas the sinuses were separated into individual regions. The water volume fraction on each surface was recorded during the simulation, which showed rapid coverage (eg, t = 0.1 seconds) across the left septum, turbinate, and left ethmoid walls. At t = 0.3 seconds the left main nasal passage is primarily covered, and the overflow into the left maxillary sinus is shown to occur in the anterior region. The nasopharynx showed very low coverage, while the soft palate, which closed the nasal airway, is covered entirely at t = 2.0 seconds. The results at t = 0.5 seconds to t = 3.0 seconds confirm the spread of liquid travelling along the floor of the right nasal cavity and inferior turbinate.

Only a small portion of flow enters the sinuses of the right nasal cavity: the anterior surfaces of the right maxillary sinus.

Water surface coverage profiles

The water surface coverage for each region as a percentage of the region's total surface area is plotted in Figure 7. In the left nasal cavity, the main nasal passage walls were nearly completely covered (>80%, with the left vestibule = 100%), whereas the ethmoid (40% coverage) and maxillary sinuses (30%) received the most coverage out of the sinuses. Negligible amounts (<1%) reached the sphenoid and frontal sinuses. In the right nasal cavity, the surface coverage began at approximately t = 0.4 seconds with relatively constant values between t = 0.5 seconds and t = 2.0 seconds. The highest coverage was found in the right vestibule (up to 100%) due to the liquid exiting the nostril. Less than 10% surface coverage was found for the right sinus walls.

WSS profiles

The averaged surface WSS distribution for each region is plotted in Figure 8. High WSSs were found at the vestibule (left and right approximately 5 Pa) and left middle turbinate (5.5 Pa). The relatively constant region between t = 0.5 seconds and t = 2.0 seconds coincided with the water surface coverage as well as the jet flow stream profile (Fig. 1D). The left nasol nasal cavity exhibited consistently higher WSS to that of the right nasal cavity. Negligible WSS was found in the sinuses of both cavities (<1.5 Pa).

Discussion

Evaluating the performance of nasal irrigation is challenging because of the rapid process of dealing with multiphase mixing of a liquid and air. The computational modeling provided highly detailed results which revealed the physical behavior of nasal irrigation that underlies its performance to distribute to the correct regions. The significant difference in densities of the 2 phases (liquid and gas/air) involved means that the liquid phase’s momentum will dominate the gas (air) phase and that extrapolation of the current results and behavior to different scenarios (eg, squeezing force, larger liquid volumes, head angles) can be made with confidence by keeping this notion in mind.

An initial jet of 5 mm was used, and in practice, this will nearly always lead to impingement on the surrounding vestibular walls and nasal valve, due to the jet diameter size relative to the nasal geometry. A thinner jet could lead to direct entry through the nasal valve without initial vestibular wall impingement. This, however, increases the variability in patient use/administration because it is significantly influenced by insertion location and orientation. A thinner jet also needs to increase its velocity to achieve the same mass flow rate for a larger diameter jet, leading to sharper impingement on the vestibular wall. A larger jet diameter can reduce patient variability, improve jet dispersion, and increase the liquid overfilling the anterior region more rapidly.

The orientation of the nozzle also influences the initial jet flow impingement, particularly for the ethmoid sinuses. As the liquid begins to fill the anterior nasal cavity, the jet orientation influence diminishes. Despite the favorable orientation toward the frontal sinuses, no liquid penetrated this region, a finding found in previous cadaveric models, likely due to the restriction from the narrow and convoluted frontal recess pathway.

The results show that liquid entry into the maxillary sinus relies on overflow from the nasal cavity because it is positioned almost perpendicularly to the flow. This supports the results of Grobler et al., who found that the size of the ostium opening influenced sinus entry. Furthermore, entry into the sphenoid sinuses was not shown in this study, but based on the principle of mass conservation, a more considerable amount of liquid with sufficiently high momentum can overcome the gravitational force and losses.
FIGURE 6. Nasal cavity surfaces were (A) unwrapped and the instantaneous surface coverage of the water volume fraction is shown at time (B) $t = 0.1$ seconds, (C) $t = 0.3$ seconds, (D) $t = 0.5$ seconds, (E) $t = 1.0$ second, (F) $t = 2.0$ seconds, and (G) $t = 3.0$ seconds. Please refer to supplementary video demonstrating full surface coverage mapping animation.
into the right nasal cavity, through the choanae. This confirms the results from Govindaraju et al., who showed that irrigation with volumes of 150 and 200 mL led to better sinus penetration than 100 mL for postoperative patients irrespective of head position. Craig et al. used CFD to demonstrate that sphenoid sinus penetration is best achieved through the nose-to-ceiling irrigation position.

In the right nasal chamber, more liquid passed along the floor and the lateral walls of the nasal cavity. This is attributed to the centrifugal force produced as the liquid swirls around the posterior nasopharynx performing a U-turn. This also enhanced entry of fluid into the right maxillary sinus. The velocity and WSSs were lower than in the left chamber. This suggests the nasal chamber containing the squeeze bottle experienced the greatest liquid surface coverage and highest WSS. Furthermore, head tilt toward the nasal chamber contralateral to the bottle may be ineffectual for achieving high WSS but would increase liquid volume flow.

The results of this study developed quantitative measures for evaluating nasal irrigation and provided insight into the mechanisms underlying the physical behavior of the liquid jet. These included: (1) liquid momentum force competing against a gravitational force, which relates to head tilt and its influence; and (2) liquid overflow from the main nasal passage into the sinuses, which relates to ostia size. As an example, the 45-degree head tilt orientation was aimed at improving sphenoid sinus penetration, but despite this, the ethmoid sinuses experienced 40% surface coverage, while less than 1% surface coverage was found in the sphenoid sinuses, suggesting that the liquid volume being injected is a more sensitive parameter than head tilt orientation.
This study expands on the CFD literature with several technological innovations. Visualization of the 3D nasal cavity is exceptionally challenging due to its highly curved and overlapping surfaces, and even when a computational 3D software is used to rotate the model to obtain the desired view, not all surfaces can be viewed adequately. This study presented the 3D model including all paranasal sinuses into a 2D representation, a technique that has yet to be used to incorporate the paranasal sinuses.

A second challenge is quantifying the effectiveness of the nasal irrigation. We developed a new quantitative analysis technique for determining sinonasal surface coverage of nasal irrigation, residence times across the mucosal surfaces, and shearing force of irrigation. Although it is expected that the surface coverage method could be adopted by future computational studies of nasal irrigation, it can be adopted by endoscopic video recordings of nasal irrigation, where each video frame is image-processed to pick up the surface coverage over time to obtain similar plots to Figure 7.

**Summary**

The physical mechanism of irrigation of a liquid formulation injected into the nasal cavity via a squeeze bottle was shown. The fluid dynamics governing the liquid jet flow as it passed through the nasal cavity was described. The key features found were as follows:
impingement on the nasal vestibule walls, before filling the vestibule;
the jet flow momentum (a combination of velocity and liquid mass/volume) must overcome gravitational forces to reach the nasopharynx;
flow into the ethmoid and maxillary sinuses was more likely than the frontal and sphenoid because the liquid jet can fill the adjacent spaces more readily; and
flow into the sinuses was produced from liquid overflowing from the main nasal passage, rather than direct jet entry.

To enhance overall jet dispersion, the results suggest that a larger jet diameter will reduce initial narrow vestibular impingement and enhance the liquid jet dispersion over a larger area. This leads to a larger liquid volume that will enhance the liquid overflow into the sinuses while also overcoming gravitational forces.

It is expected that a larger cohort of computational models may be undertaken using the existing evaluation method to investigate the influences of head tilt, liquid volume, intensity, and duration of flow. Future studies may also provide insight and characterize the flow of nasal irrigation in order to develop new ideas on device design and delivery to achieve greater paranasal sinus coverage.

Conclusion

Detailed physical mechanisms of liquid irrigation injected from a commonly used squeeze bottle were shown. Ipsilateral maxillary and ethmoid sinus penetration are primarily due to overflow rather than direct jet entry, confirming the recommendation of larger volumes of irrigation to “flood” the sinus ostia.

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References