Atrophic rhinitis: A CFD study of air conditioning in the nasal cavity

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ABSTRACT

Atrophic rhinitis is a chronic disease of the nasal mucosa. The disease is characterized by abnormally wide nasal cavities and its main symptoms are dryness, crusting, atrophy, fetor, and a paradoxical sensation of nasal congestion. The etiology of the disease remains unknown. Here, we propose that excessive evaporation of the mucous layer is the basis for the relentless nature of this disease. Airflow and water and heat transport were simulated using computational fluid dynamics (CFD) techniques. The nasal geometry of an atrophic rhinitis patient was acquired from computed tomography (CT) scans before and after a procedure to narrow the nasal cavity. Simulations of air conditioning in the atrophic nose were compared to similar computations performed within the nasal geometries of 4 healthy humans. The excessively wide cavity of the patient generated abnormal flow patterns, which led to abnormal patterns of water fluxes across the wall. Geometrically, the atrophic nose had a much lower surface area to volume ratio than the healthy nasal passages, which increased water fluxes per unit area. Nevertheless, the simulations indicated that the atrophic nose did not condition inspired air as effectively as the healthy geometries. These simulations of water transport in the nasal cavity are consistent with the hypothesis that excessive evaporation of mucus plays a key role in the pathophysiology of atrophic rhinitis. We...
conclude that the main goals of a surgery to treat atrophic rhinitis should be (i) to restore the original surface area of the nose, (ii) to restore the physiological airflow distribution, and (iii) to create symmetric cavities.

**Keywords:** nasal physiology, empty nose syndrome, ozena, CFD simulations in the human nose, nasal epithelium.
INTRODUCTION

Atrophic rhinitis (AR), sometimes referred to as ozena, is a chronic nasal mucosal disease of unknown etiology. AR is characterized by progressive mucosal atrophy, nasal crusting, dryness, fetor, and enlarged nasal space with a paradoxical sensation of nasal congestion (38). The disease is often accompanied by sinusitis, depression, facial pain, epistaxis, anosmia, and septal perforation (38). In some patients the fetor is so unbearable, even to spouses and friends, that the patient may suffer social ostracization (47).

The incidence of primary atrophic rhinitis decreased markedly in the 20th century, but it is still frequently found in underdeveloped countries, and is particularly prominent in India. In contrast, secondary atrophic rhinitis is encountered by rhinologists all over the world (27, 38). In a comprehensive review of the disease, Moore and Kern (38) have shown that secondary AR patients usually have a history of destructive nasal surgery (e.g., turbinectomy), but the disease may also develop after trauma, chronic rhinosinusitis, irradiation, and chronic granulomatosis.

Clinical management of the disease is limited and frequently unsatisfactory. Currently, no definitive solution has been defined. Patients need to irrigate their noses 3 or 4 times a day without cessation, since symptoms return when the artificial humidification is discontinued (38). Several surgical treatments have been evaluated, including some that aggravated the condition, such as removal of the turbinates and radical sinus surgery (18). Since the beginning of the 20th century, it is known that patients benefit from narrowing the lumen of the cavity and a range of different techniques have been proposed (11, 49). These procedures usually provide relief of nasal
crusting and other symptoms, but permanent results are not always maintained due to the absorption or extrusion of the implants. The only procedure known to provide permanent relief from the symptoms is abolition of nasal respiration by surgical closure of the nostrils (Young’s procedure) (54, 55). However, many patients do not accept this surgery, owing to the discomfort of breathing through the mouth and to the hyponasal voice (46, 54).

The cause of primary atrophic rhinitis is unknown. Several hypotheses have been proposed, including nutritional deficiencies, heredity, endocrine factors, and bacterial infection with *Klebsiella ozaenae* and *Bacillus foetidus* (11, 38). The disease has also been observed in sheep, cattle, and pigs, causing significant financial loss in the pork industry (9, 15, 32). In pigs, there is evidence that the disease is triggered by infection by the bacteria *Pasteurella multocida* and *Bordetella bronchiseptica*. However, in humans it is difficult to determine if the infecting organisms cause the tissue destruction or are only opportunistic invaders.

The healing properties of cavity narrowing procedures and Young’s procedure suggest a role for nasal airflow in the pathophysiology of the disease. We propose that in humans atrophic rhinitis is sustained by abnormal water loss from the mucosa due to a non-physiologic nasal airflow. Concomitant factors debilitating the mucosa, such as nutritional deficiency, may also play a role, but it is our assertion that increased mucus evaporation and an abnormal distribution of water fluxes are the basis for the relentless nature of the disease. This hypothesis was first proposed by Wachsberger (49), but it has never been tested and seems to have been forgotten, since we found no comments about this idea after the 1960s (18).
A body of indirect evidence in the literature supports this argument. First, genuine atrophic rhinitis has never been observed in a narrow nose (49), which is consistent with abnormal flow patterns playing a role in the pathophysiology of the disease. Second, Girgis (18) demonstrated that if a patient with atrophic rhinitis blocks his nostrils with pieces of cotton for 24 hours, the nasal mucosa will present an entirely different picture on removal of the plugs; it becomes moist and less pale and the crusts become loosened. Third, crusts are never observed in the paranasal sinuses, where the drying effect of airflow is less vigorous than in the nasal cavity (49). Finally, Dutt and Kameswaran’s observation (11) that primary AR seems to have a high prevalence in the arid regions bordering the great deserts of Saudi Arabia suggests that low absolute humidity of the air may trigger AR in susceptible populations.

Further evidence is provided by cases of unilateral atrophic rhinitis related to a septal deviation. It has been observed that the air-humidifying capacity of the nose is time-dependent because when a continuous air stream is drawn through the nose, air becomes progressively cooler and drier at the outlet (8). Therefore, we suggest that unilateral AR associated with septal deviation may be explained as follows: if the cavity on the concave side of the septum is too large, air will flow mostly through this patent side, subjecting it to a permanent water and temperature gradient. If the water gradient is sufficiently large or the mucosa unhealthy, the mucous layer may dry in regions of high water flux, leading to crust formation and predisposing to infection. Due to the lack of a cyclic closure of the affected side, the continuous airflow is a continuous burden to the mucosa, which will not heal unless artificial irrigation is instituted or airflow artificially obtunded. Clinical observations support this idea: Bunnag and co-workers noted that in
AR patients with marked septal deviation, crust is found only in the wider side of the nasal cavity (5); Gupta reported improvement in the symptoms of unilateral atrophic rhinitis after the septal deviation was corrected surgically (20). This improvement may be due to the more uniform division of the humidification task between the cavities after surgery. This reasoning suggests that the nasal cycle may have an important role in allowing each cavity to recover after it has been responsible for warming and humidifying the air for a while. This duty of the nasal cycle in providing a rest period for recovery of the nasal epithelium from any damage caused by the airflow has also been proposed by others (4, 12).

The objective of this research was to investigate airflow, water transport and heat transfer in the nose of an atrophic rhinitis patient who underwent a surgical procedure to narrow his nasal cavity. We also performed calculations of the air conditioning process in the noses of 4 healthy humans to establish a basis for comparison. Our aim was to test the hypothesis that the pathophysiology of AR is associated with excessive evaporation of the mucous layer as well as to devise strategies to improve the outcome of cavity-narrowing procedures in the treatment of AR.

MATERIALS AND METHODS

A 26-year old Caucasian male was diagnosed with primary atrophic rhinitis in the Santa Casa hospital in Belo Horizonte, Brazil. His symptoms were: aggressive fetor; nasal crusting; mucosal atrophy; rhinorrhea; resorption of the turbinates resulting in a large nasal cavity; and a paradoxical sensation of nasal congestion. A marked atrophy of the inferior and middle turbinates yielded roomy nasal passages, especially in the left
side. Both sides were affected by the disease, but the right cavity was not as wide as the left due to a septal deviation. The patient reported having symptoms since he was 13 years old and that his symptoms had not responded to repeated courses of antibiotics.

The patient underwent a nasal-cavity-narrowing procedure. Rib cartilage was implanted under the mucosa along the floor of the nose and a septum spur was removed. At the time of surgery, it was reasoned that the septal deviation assisted in maintaining the right cavity narrow, therefore the deviation was not corrected. Cartilage was implanted mostly in the left side as an effort to narrow the most patent side. Computerized tomography (CT) scans of the nasal passages were taken before and 6 weeks after surgery. Axial slices with thickness of 1.0 mm and an increment of 0.6 mm were used, resulting in 109 cross-sections.

The nasal geometry of the 4 healthy adult humans used in this study came from coronal cross-sections of hexagonal meshes that had been created at The Hamner Institutes for Health Sciences (Research Triangle Park, NC, USA) from MRI scans of 3 mm spacing (43). These MRI scans were carefully selected from a sample of 17 scans of healthy volunteers to represent complete nasal passages and a broad range of surface area to volume ratios.

The nasal geometries were reconstructed in three dimensions using medical imaging software (Mimics®, Materialise, Ann Arbor, MI) and meshed with tetrahedral elements (ICEM-CFD®, Ansys, Inc., Canonsburg, PA). The quality of the tetrahedra was checked using ICEM-CFD® to ensure that all cells had an aspect ratio larger than 0.3, a value needed to avoid distorted elements and optimize the accuracy of the numerical simulations. The nasal cavity was modeled as a rigid structure.
Steady-state inspiratory air, heat, and water transport were simulated using Fluent® (Fluent, Inc., Lebanon, NH). Pressure-inlet and pressure-outlet boundary conditions were used to mimic the pressure-driven respiration occurring in real life. A constant pressure drop was imposed equally on both nostrils of each reconstructed nose and chosen (using the target-mass-flow-rate feature of Fluent®) such that the total volumetric flow through the nostrils was 250 ml/s, corresponding to resting breathing (2). A no-slip (zero velocity) boundary condition was assumed at the airway walls.

The experimental literature on nasal respiration suggests that airflow is primarily laminar in healthy adults during resting breathing (7, 21, 30). Likewise, most published CFD investigations assume that nasal airflow is laminar at rest (3, 31, 40, 48, 56). However, there are no experimental data on the airflow patterns in abnormally wide nasal cavities, such as noses affected by AR. Also, the flow rate at which turbulence effects become important in healthy noses is still uncertain since some researchers have observed a partially turbulent flow even at low air velocities (17, 45). For this seminal study, we assumed that nasal airflow is laminar in normal and abnormal geometries. For healthy nasal cavities, this hypothesis has been shown to provide accurate predictions (31, 48).

Lindemann and coworkers (34) measured mucosa temperature during the respiratory cycle in 15 healthy volunteers at room conditions of (25 ± 1)°C and (30 ± 4)% relative humidity (RH). They reported that during the course of inspiration temperature decreased from (32.5 ± 1.1)°C to (30.2 ± 1.7)°C in the nasal valve and from (34.4 ± 1.1)°C to (33.2 ± 2.3)°C in the nasopharynx. During expiration, the mucosal temperature increased back to original values. Thus, we adopted a mean value of 32.6°C for the mucosal temperature during inspiration. Ambient air was set to 20°C at the nostrils, and outflow boundary
conditions were applied to the outlet (see Appendix A for details). To account for the cooling effect of water evaporation, our heat flux calculation included a term of water flux times the latent heat of evaporation, as proposed by Naftali et al. (40) (Appendix A).

The respiratory epithelium is coated with mucus, and thus air was assumed to be at 100% RH at the air-tissue boundary of the main nasal cavity. However, the nasal vestibule is lined with squamous epithelium, and therefore water flux was set to zero in this region. To define the vestibule, we created a curve on the nasal surface by intersecting the nasal geometry with a cylinder (diameter = 20mm) whose axis is perpendicular to the septum. This curve was a good first-approximation of the limen nasi, the anatomical ridge marking the boundary between the nasal cavity proper and the vestibule (33). The curve was then used to split the nasal surface, defining a region covered with squamous epithelium (nasal vestibule) and a region covered with respiratory epithelium (proper nasal cavity), where the above-mentioned boundary conditions were defined. Ambient air was considered to be at 50% RH, while outflow boundary conditions were applied to the outlet (see Appendix A).

Nasal resistance ($R_{\text{nose}}$), defined as $R_{\text{nose}} = \Delta p/Q$, where $\Delta p$ is the pressure drop in Pascals (Pa) and $Q$ is the flow rate in milliliters per second (ml/s), was computed from the simulation results and compared to literature data obtained by rhinomanometry (38). Mesh density tests were conducted to ensure grid-independence of all results, and the data reported here were obtained in meshes of 900,000 to 1,300,000 tetra cells. More details on the differential equations solved in Fluent®, computational algorithms employed, and boundary conditions and physical properties utilized can be found in Appendix A.
RESULTS

To characterize the geometry of the atrophic nose and compare it with healthy cavities, cross-sectional areas of coronal sections from the nostrils to the beginning of the nasopharynx were calculated (Fig. 1). The cross-sectional areas of the healthy nasal airways were at a minimum approximately 15 mm posterior to the nostrils. This region, known as the nasal valve, corresponds to the level prior to and including the anterior end of the inferior turbinate and it is responsible for most of the resistance to airflow (22, 25, 42). Posterior to the valve, the cross-sectional area increased rapidly to a plateau value that was maintained through most of the turbinate region. Approaching the choanae, the turbinates receded, the cross-sections gradually became two oval empty spaces, and the cross-sectional areas increased rapidly.

The before-surgery nasal geometry of the atrophic rhinitis subject was remarkably different. The cross-sectional area increased steadily from the nostrils to the end-turbinate region (except for a small decline at the nasal valve), being at least twice the normal value throughout most of the turbinate region (Fig. 1). After implantation of rib cartilage under the mucosa on the floor of the nose, the cross-sectional areas of the anterior portion became similar to normal. The posterior part, however, was not modified during surgery and, therefore, remained wide. An expansion of both inferior turbinates was observed throughout the nasal cavity after surgery (Fig. 2).

Volumes and surface areas of the models were calculated for each nasal cavity from the nostrils to the end of the septum (Table 1). The atrophic nose had a smaller surface area and a larger volume than the normal subjects. Surgery decreased the volume,
but did not increase the surface area. A useful measurement to determine whether a nasal cavity is narrow or wide is the surface area to volume ratio (SAVR). The narrower the cavity is, the larger the SAVR is, and vice-versa. Our sample of 4 healthy humans had a mean SAVR of $(0.97 \pm 0.14)$ mm$^{-1}$ for the left and right cavities combined. This value is in good agreement with a recent study by Yokley (53) who used CT scans to calculate SAVRs in a much larger sample (40 European Americans and 9 African Americans) of healthy volunteers. He found SAVR = $(1.05 \pm 0.23)$ mm$^{-1}$ in European descendents and SAVR = $(1.03 \pm 0.29)$ mm$^{-1}$ in African ones. In contrast, before surgery the atrophic nose had a SAVR of 0.39 mm$^{-1}$, which increased to 0.50 mm$^{-1}$ after surgery.

Several investigators have reported that in a normal nose air flows mainly near the septum, especially along the floor of the nose and between the septum and the middle meatus (30, 42, 48, 52). A small percentage of air flows through the meatuses and the olfactory slit. The turbinates have been reported to have a streamlining effect, directing the flow to the nasopharynx, leaving the airflow distribution almost unchanged as flow rate increases (21, 31, 42, 48). In contrast, our simulations displayed a very different pattern in the atrophic nasal cavity (Fig. 2). We predicted that in an ‘empty’ nose the air flows mainly through the upper half of the cavity, while a low-velocity eddy was observed in the inferior portion.

Our simulations predicted that the atrophic nose did not warm or humidify the air as effectively as the healthy nasal airways studied (Table 2). Simulated air temperature was already within 1.5°C of the mucosal temperature at the mid-turbinate region for the normal subjects (40-50 mm after the nostrils; Fig. 3(a)). Meanwhile, at the same location, the temperature was still 27 to 28°C in the before-surgery atrophic nose, which is 4.6 to
5.6°C below the mucosal temperature. After surgery, the airflow simulations predicted the nose had partially recovered its capacity to warm the inspired air (Fig. 3(a); Table 2). A similar behavior was predicted for air humidification (Fig. 3(b); Table 2).

To provide a partial test of our hypothesis that AR is related to exaggerated evaporation of the mucous layer, we computed water fluxes per unit area throughout the nasal mucosa (Figs. 4, 5, and 6; Table 3). In the normal noses studied, inspired air was warmed and humidified mainly in the anterior-inferior portion of the cavity (Fig. 3), in agreement with previous reports (28, 40), and thus this was the region with the largest heat and water fluxes (Figs. 5 and 6). In contrast, the disturbed flow pattern and smaller surface area of the atrophic nose predicted a very different scenario. Here, large water fluxes were spread throughout most of the nasal cavity (Figs. 5 and 6), with hotspots along the superior part of the cavity and on the middle turbinate (Fig. 4). Past the nasal valve, heat and water fluxes were higher in the atrophic geometries than in the normal subjects (Fig. 5). In particular, the AR nose had much higher heat and water fluxes in the nasopharynx as compared to the normal noses (Table 3).

After surgery the atrophic nose had a significant imbalance in the partitioning of airflow (Table 4). While 64% of the air flowed through the left cavity prior to surgery, this fraction increased to 91% post-operatively. Consequently, the left cavity carried out most of the air conditioning, leading to much higher heat and water fluxes in this side than in the right side, and preventing a desired reduction in water flux levels on the left side (Table 3). This imbalance in airflow distribution was partially due to a post-surgery constriction in the right side caused by excess implantation of cartilage at the nasal valve area (more details below).
Post-operative CT scans depicted the atrophic nose six weeks after the procedure. At this stage, the patient reported nasal obstruction and anosmia, but no crusting, rhinorrhea, or fetor. Six months after surgery, partial resorption of the implant was noted. The patient was satisfied with the absence of stench, but endoscopy revealed crust formation on the posterior portion of the septum, between the septum and the superior turbinate, and along the medial aspect of the middle and inferior turbinates on the left side. There were fewer crusts in the right cavity and these were located on the proximal aspect of the middle turbinate and in the upper-posterior region. The larger amount of crusts on the left side correlated with the higher left-side flow rate and water flux levels (Tables 3 and 4). The post-operative total amount of crusts seemed to be smaller than the pre-operative, which might be related to the improvement of the fetor six months after the operation. Anosmia and nasal obstruction were persistent symptoms.

Despite the patient’s pre-operative complaint of nasal congestion, the calculated nasal resistance of the AR nose was smaller than the values predicted for the 4 healthy noses before surgery (Table 2; Fig. 7). On the other hand, the post-operative nasal resistance was predicted to be twice as large as the average for our 4 healthy noses. This higher post-operative resistance was partially due to the cavity-narrowing procedure and partially due to the different positions of the soft palate in the before and after CT scans, which led to a narrower nasopharynx in the post-surgery geometry. The rise in nasal resistance a month and a half post-operatively was expected: the surgeon had anticipated that partial resorption of the implants would occur and implanted excess cartilage. Due to the implant resorption, nasal resistance most likely diminished since the CT scans were taken, but no quantitative assessment could be made due to the lack of a rhinomanometer.
in our Brazilian clinic. Thus, our data suggest that the pre-operative complaint of nasal congestion was due to loss of sensory receptors, in agreement with rhinomanometry data collected by Moore and Kern (38) for 135 AR patients, while the post-operative nasal congestion may be associated to the increased nasal resistance.

DISCUSSION

The human nose is responsible for warming, humidifying, and cleaning inspired air. To accomplish this task, the nasal mucosa is coated with a thin layer of mucus, which traps airborne particles as well as moistens the air by evaporation. Atrophic rhinitis is a chronic disease of the nasal mucosa and its etiology is still unknown. The disease is characterized by progressive atrophy, nasal crusting, dryness, fetor, enlargement of the nasal space, and a paradoxical sensation of nasal congestion. Two comprehensive reviews of AR have recently been published, and the readers are referred to them as detailed descriptions of this disease (11, 38).

We simulated the airflow and transport processes that occur in the nasal cavities of 4 healthy humans and one AR patient. We found that, while air humidification occurred mainly in the anterior-inferior portion of the cavity in the healthy noses studied (Figs. 5 and 6), high water fluxes were more spread out in the AR nose, with hotspots at the superior nasal cavity and on the proximal aspect of the middle turbinate (Fig. 4). These hotspots correlated with the regions where crusting is more frequently observed in AR patients in our Brazilian clinic. Other investigators have also reported that the middle turbinate is more frequently affected than the inferior turbinate (23, 47). Ssali (47) stated that in the early stage of the disease crusts may be confined to the middle and superior
turbinates, but one hardly ever finds crusts confined to the inferior turbinate without involvement of the middle one. These findings suggest that the superior air current that was predicted in our simulations (Fig. 2) may be a prevailing feature of AR, leading to crust formation mainly in the upper half of the cavity. Our simulations also predicted an above-normal mucus evaporation past the nasal valve in the AR nose (Fig. 5). In particular, water fluxes were substantially higher at the nasopharynx of the atrophic nose as compared to the normal noses (Table 3). This may explain why AR is often accompanied by pharyngitis sicca, a disease characterized by atrophy of the mucous glands and absence of their secretion (11, 44).

These results are consistent with the hypothesis that abnormal patterns of mucus evaporation may play a key role in the pathophysiology of AR. The wide nasal cavity of the AR patient (demonstrated by below-normal surface-area-to-volume ratio) generated an abnormal flow pattern. This abnormal distribution of airflow, in turn, led to an increase in the water fluxes in regions that normally would not be subject to high levels of mucus evaporation, namely the upper half of the nasal cavity (Fig. 6(b)). The drying effect of the airflow would be expected to increase the viscosity of the mucus fostering the formation of crusts. These crusts may in turn impair the delicate ciliary apparatus, causing stasis of the secretion, perhaps leading to more crust formation. The lack of nasal clearance facilitates infection by opportunistic pathogens; and the fetor that characterizes the disease may come from these highly infected crusts. This reasoning was also proposed by Wachsberger (49).

Mygind et al. (39) explain how the normal nasal epithelium gradually changes from squamous epithelium to ‘pseudostratified columnar epithelium with abundant
ciliated cells’ moving from the vestibule towards the turbinates. The ciliated cells do not appear suddenly, but rather their density increases gradually going deeper into the nose. The prediction of high water flux in the anterior portion of the healthy nose (Figs. 4 and 5) suggests that ciliated cells are more predominant in regions of low water flux. Since in the atrophic nose large water fluxes were not restricted to the anterior portion of the cavity, we propose that the abnormal patterns of water fluxes in the atrophic nose may lead to replacement of ciliated cells by some other type in the respiratory epithelium. The characteristic finding of patches of squamous epithelium in the respiratory mucosa of AR patients is in agreement with this reasoning (1, 5, 11, 19). It is recognized that exposure to irritants in general can cause squamous metaplasia. Thus squamous metaplasia may occur in AR patients due to the drying effects of airflow, rather than being the root cause for the lack of mucous layer. Once the epithelium has been replaced, the patches of squamous epithelium may be expected to contribute to the shortage of mucus, stasis, and progress of the disease. More studies are needed, however, to establish a causal association between regions of high mucus evaporation and squamous metaplasia.

Atrophic rhinitis is not permanently cured by antibiotics (38). One way to control the disease is to irrigate the nose artificially, but the symptoms return whenever the irrigation is ceased. Our hypothesis may explain this relentless nature of the disease because the disease would not be expected to recede while excessive evaporation of the mucus continued. The hypothesis also suggests that closure of the nostrils (Young’s procedure) stops the disease because suturing the nostrils releases the nose from its humidification task.
The anosmia in AR patients has been proven to be a sensory problem, since electron microscopic studies have shown that these patients have atrophy of the olfactory epithelium receptors (38). Our simulations suggest that loss of these receptors may be due to the high water flux predicted at the olfactory region (Figs. 4 and 6(b)). In a healthy nose, air flows mainly along the floor and between the septum and the middle meatus (16, 48, 52). Only 10-15% of the air passes through the olfactory slit. In contrast, in the atrophic nose, most of the air flowed along the upper half of the nose (Fig. 2). Compared to the healthy nose, this abnormal airflow distribution subjects the olfactory epithelium to increased water and heat fluxes that may damage the olfactory cells by drying the epithelium.

The sensation of nasal congestion in AR has been proposed to be due to the loss of receptors for pain and temperature (38). However, this hypothesis is still unproven (38). The calculated nasal resistance for the before-surgery atrophic nose – 0.028 Pa/(ml/s) – is below the range of resistances we computed for the 4 normal cavities, namely 0.039 - 0.082 Pa/(ml/s). This finding substantiates the nomenclature ‘paradoxical’ for the complaints of nasal congestion associated with AR and is in agreement with rhinomanometry data collected by Moore and Kern in 135 AR patients (38). The mean total nasal resistance in their patients was 0.12 Pa/(ml/s), while literature reports for healthy subjects are on the order of 0.15 - 0.30 Pa/(ml/s) (38). The resistance figures calculated by CFD are somewhat lower than the ones obtained through rhinomanometry, as also found in other CFD studies (50). However, it should be borne in mind that by convention rhinomanometry calculates nasal resistance at a trans-nasal pressure drop of 150 Pa (6). The simulations presented in this study were based on resting airflow rates,
where the trans-nasal pressure drop is considerably lower. The non-linear shape of the pressure-flow curve for nasal airflow means that the resistance figures calculated in this work are not directly comparable to rhinomanometry. Nevertheless, both methods are consistent in predicting reduced nasal resistances for AR patients.

The high efficiency of a healthy nasal cavity for warming and humidifying the inspired air is well recognized (8, 28, 29, 36, 40). The simulations presented in this study predicted that at rest inspired air was already within 1.5°C of the mucosa temperature ($T_{mucosa} = 32.6°C$) at the middle of the normal turbinate region (Fig. 3(a)). Due to the abnormal patency of the atrophic nose, however, air was still 4.6 to 5.6°C colder than $T_{mucosa}$ ($27°C < T_{air} < 28°C$) when it reached the same location prior to surgery. While in the normal noses air exited the nasopharynx at $T_{air} \approx T_{mucosa}$ and with ~36 grams of water per cubic meter of air, in the before-surgery atrophic nose air was still ~3°C below $T_{mucosa}$ and the water content was still 30g/m³ of air (Table 2). These predictions are consistent with experimental measurements by Drettner et al. (10), who measured the air conditioning capacity of normal and pathological noses, and found that atrophic noses do not condition the air as effectively as normal ones. Also in agreement with our simulations, Lindemann et al. (35) found a decreased capacity to warm inspired air in cavities widened through aggressive sinus surgery with resection of the turbinates. Interestingly, dryness and crusting are also frequent complaints of these patients (35).

Our simulations predicted that the cavity-narrowing procedure improved the air-conditioning properties of the atrophic nose. At the nasopharynx level, air was 1.2°C warmer and 2.5% more humid post-operatively (Table 2). The surgery, however, failed to restore the normal airflow and water flux patterns (Figs. 2 and 4). Our analysis of the
water transport six weeks after surgery suggests that mucus evaporation increased post-operatively in the left cavity (Figs. 5 and 6; Table 3). This increase was partially due to the great imbalance in airflow partitioning between the two cavities after surgery (Table 4). Six months after surgery, crusts were observed mostly in the left side, in agreement with the higher airflow and higher water flux calculated for this side of the nose. At that time it was observed that resorption of the implant widened an anterior constriction that had occurred on the right cavity due to the implant, partially reducing the imbalance in airflow distribution between the two cavities. However, it is unlikely that this redistribution has been sufficient to bring the water flux levels back to their normal values. Therefore, our analysis suggests that the surgery was not a final cure for this patient because water flux through the mucosa remained abnormally high and abnormally distributed. At the present time, the patient reports being satisfied with the surgical outcome because his main complaint (the fetor) has resolved, although crusts are still present.

At first sight, there seems to be a contradiction between the higher magnitude of heat and water fluxes in the atrophic nose and incomplete air conditioning as compared to the normal subjects (Table 2, Fig. 5). This apparent discrepancy is explained by the reduced surface area available for heat and water exchange in the atrophic nose. This effectively means that, despite the increased levels of heat and water fluxes (per unit area), the overall rate of heat and moisture transfer from tissue to air in the atrophic geometries is lower than normal, leading to incomplete conditioning of inspired air. This finding suggests that reconstructive nasal surgeries in AR should target to augment the nasal surface area to avoid excessive mucus evaporation and drying.
Finally, we would like to discuss some limitations of this seminal investigation. First, simulations were conducted only for the inhalation part of the respiratory cycle. It is known that approximately 1/3 of the heat and humidity transferred from mucosa to inspired air is recovered during exhalation (52). Therefore, humidity recovery during expiration needs to be included in future studies to confirm that the patterns of increased mucus evaporation in AR noses observed here are not affected. Second, the cyclic changes of flow direction and mucosal temperature during respiration were approximated by an average, steady-state process. Theoretical arguments support this approach with regard to the airflow patterns (31), but the dependence of mucosal temperature on airflow patterns is still unclear. Recent advances in computation capacity are just beginning to allow the study of time-dependent nasal airflow (26, 37), so that this hypothesis may be tested soon.

Third, we assumed that nasal airflow is laminar in AR and normal noses. There is evidence that the airflow is indeed laminar for resting flow rates in healthy noses (7, 21, 30, 31, 48), but it is possible that the flow is more turbulent in the wide cavities of AR patients. To clarify this issue, we are currently investigating the airflow patterns in a physical replica of the AR nose experimentally. The general conclusions drawn in this paper, however, would not change if airflow were found to be turbulent in the atrophic nose, since turbulence would increase the drying effect of the airflow, reinforcing the hypothesis that excessive evaporation of the mucous layer plays a key role in the pathophysiology of atrophic rhinitis.
CONCLUSION

The airflow and water vapor transport simulations presented in this article support the hypothesis that atrophic rhinitis is related to excessive evaporation of the mucous lining. We suggest that three main factors contribute to increased water flux in the mucosa of these patients. First, we found that the lack of turbinates led to an abnormal airflow distribution. Air flowed mainly along the top half of the nose, substantially increasing the humidification burden on this region. Second, we found that the atrophy process reduced the surface area available for water transfer, increasing flux per unit area. Third, we found that a unilateral obstruction concentrates air humidification in the most patent side, and thus contributes to increased water flux in this side. Therefore, our results suggest that the main goals of a surgery to treat atrophic rhinitis should be (i) to restore the original surface area of the nose, (ii) to restore the physiological airflow distribution, and (iii) to create symmetric cavities. These three strategies would have the overall effect of minimizing the water fluxes per unit area and re-establishing the physiological pattern of restricting high water fluxes to the anterior-inferior portion of the nose. A procedure that seems to fit these criteria is the reconstruction of the inferior and middle turbinates (41).
APPENDIX A
DESCRIPTION OF THE COMPUTATIONAL METHOD

The conservation of mass and momentum for laminar, incompressible flow are described, respectively, by the equations

\[ \nabla \cdot \vec{u} = 0 , \]
\[ \rho \frac{\partial \vec{u}}{\partial t} + \rho (\vec{u} \cdot \nabla) \vec{u} = -\nabla p + \mu \nabla^2 \vec{u} , \]

where \( \vec{u} = \vec{u}(x, y, z, t) \) is the velocity vector, \( t \) is time, \( \rho \) is fluid density, and \( \mu \) is dynamic viscosity \( (13, 51) \). In our simulations we adopted \( \rho = 1.20 \text{ kg/m}^3 \) and \( \mu = 1.9 \times 10^{-5} \text{ kg/ms} \) \( (24, 40) \).

Heat transfer is governed by the equation of energy conservation

\[ \frac{\partial T}{\partial t} + (\vec{u} \cdot \nabla) T = \frac{k}{\rho c_p} \nabla^2 T , \]

where \( T = T(x, y, z, t) \) is temperature, \( c_p = 1005.9 \text{ J/kg.K} \) is the specific heat and \( k = 0.0268 \text{ W/m.K} \) is the thermal conductivity of air \( (40) \). The transport of moisture from the mucosa to air is governed by the convection-diffusion equation:

\[ \frac{\partial}{\partial t} c_{H_2O} + (\vec{u} \cdot \nabla) c_{H_2O} = D_{H_2O} \nabla^2 c_{H_2O} , \]

where \( c_{H_2O} = c_{H_2O}(x, y, z, t) \) is the water vapor concentration in air and \( D_{H_2O} = 2.6 \times 10^{-5} \text{ m}^2/\text{s} \) is the mass-diffusivity of water vapor in air \( (24, 40) \).
Steady-state versions of these equations were solved on a dual-processor workstation (Dell Precision, Intel Xeon 3.60 GHz, 3.93 GB of RAM) using Fluent® 6.2.16 (Fluent Inc., Lebanon, NH). Fluent® uses the finite volume method to solve the differential equations numerically. The segregated solver with SIMPLEC pressure-velocity coupling and second-order, upwind discretization were utilized for solution of the above equations (14). Since the physical properties of the air-water vapor mixture were assumed constant, an uncoupled solution strategy was employed, namely the flow field was obtained first and then the energy conservation and convection-diffusion equations were solved.

For the healthy-nose meshes (~10^6 tetrahedral cells), Fluent® took ~2 hours to solve the flow field (~ 450 iterations) and ~7 minutes to solve the heat/water transport equations (~25 iterations). The atrophic-nose meshes required typically twice as many iterations/CPU time to converge, despite having approximately the same number of cells. Convergence was confirmed by small residuals (continuity: ≈10^{-3}; velocities: ≈ 5x10^{-5}; energy equation: ≈ 3x10^{-7}; convection diffusion equation: ≈ 7x10^{-6}) and by monitoring the flow rate, temperature, and RH at the outlet surface for stabilization.

Relative humidity (RH) is the ratio of the partial pressure of water vapor actually present in the mixture (\(p_{H_2O}\)) to the water vapor pressure of saturated air at the same temperature (\(p_{H_2O,S}\)). The latter is calculated in Fluent® from experimental data, while the former is obtained in Fluent® from the water concentration in air (\(c_{H_2O}\)) using the ideal-gas law \(p_{H_2O} = RTc_{H_2O}/MM_{H_2O}\), where \(R = 8.31\) Pa.m^3/mol.K is the universal gas constant and \(MM_{H_2O} = 0.018\) kg/mol is the molecular mass of water. Our boundary
condition of 100% RH at the walls (at 32.6°C) was defined as \( c_{H_2O} |_{WALL} = 0.03694 \) kg/m³. For the inlet, 50% RH (at 20°C) corresponds to \( c_{H_2O} |_{INLET} = 0.00869 \) kg/m³. The ‘outflow’ boundary condition in Fluent imposes \((\nabla T \cdot \vec{n}) = 0\) and \((\nabla c_{H_2O} \cdot \vec{n}) = 0\) at the outlet, where \( \vec{n} \) is a unit vector normal to the surface. Any backflow at the outlet was assumed to be at 32.6°C and 100% RH.

Fluent® 6.2 does not provide the option of plotting species flux \((Flux_{H_2O} = -D_{H_2O} (\vec{n} \cdot \nabla c_{H_2O})_{wall})\) through the domain walls. Therefore, a User-Defined Function was written in Fluent® to make the water flux data available as a User-Defined Memory Variable. To take into account that water evaporation increases the heat lost by the nasal mucosa, heat flux \((Flux_{heat})\) was computed from

\[
Flux_{heat} = -k \nabla T + Flux_{H_2O} \Delta H,
\]

where \( \Delta H = 2.411 \times 10^6 \) J/kg is the latent heat of evaporation of water at nasal-tissue temperature (40).
ACKNOWLEDGEMENTS

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GRANTS

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REFERENCES


### TABLES

#### TABLE 1 – Geometrical features of our 6 human meshes.

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>REGION</th>
<th>Surface area (mm²)</th>
<th>Volume (ml)</th>
<th>SAVR (mm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heathy nose 1</td>
<td>Left cavity</td>
<td>9,900</td>
<td>9.2</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>Right cavity</td>
<td>10,190</td>
<td>8.7</td>
<td>1.17</td>
</tr>
<tr>
<td></td>
<td><strong>Both cavities</strong></td>
<td><strong>20,090</strong></td>
<td><strong>18.0</strong></td>
<td><strong>1.12</strong></td>
</tr>
<tr>
<td>Heathy nose 2</td>
<td>Left cavity</td>
<td>8,300</td>
<td>7.9</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>Right cavity</td>
<td>8,330</td>
<td>7.8</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td><strong>Both cavities</strong></td>
<td><strong>16,630</strong></td>
<td><strong>15.6</strong></td>
<td><strong>1.06</strong></td>
</tr>
<tr>
<td>Heathy nose 3</td>
<td>Left cavity</td>
<td>11,620</td>
<td>11.6</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Right cavity</td>
<td>11,510</td>
<td>15.5</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td><strong>Both cavities</strong></td>
<td><strong>23,130</strong></td>
<td><strong>27.1</strong></td>
<td><strong>0.86</strong></td>
</tr>
<tr>
<td>Heathy nose 4</td>
<td>Left cavity</td>
<td>10,240</td>
<td>13.2</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>Right cavity</td>
<td>10,380</td>
<td>11.0</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td><strong>Both cavities</strong></td>
<td><strong>20,620</strong></td>
<td><strong>24.2</strong></td>
<td><strong>0.85</strong></td>
</tr>
<tr>
<td>Atrophic pre-op</td>
<td>Left cavity</td>
<td>7,130</td>
<td>24.0</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>Right cavity</td>
<td>6,220</td>
<td>10.5</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td><strong>Both cavities</strong></td>
<td><strong>13,350</strong></td>
<td><strong>34.5</strong></td>
<td><strong>0.39</strong></td>
</tr>
<tr>
<td>Atrophic post-op</td>
<td>Left cavity</td>
<td>6,270</td>
<td>13.7</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>Right cavity</td>
<td>5,860</td>
<td>10.6</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td><strong>Both cavities</strong></td>
<td><strong>12,130</strong></td>
<td><strong>24.3</strong></td>
<td><strong>0.50</strong></td>
</tr>
</tbody>
</table>

Atrophic pre-op and atrophic post-op refer, respectively, to the pre- and post-operative geometries of the atrophic nose. SAVR is the surface-area-to-volume ratio of the nasal cavity from the nostrils to the end of the septum.
TABLE 2 – Air temperature, relative humidity (RH), and water content at the nasopharynx, and nasal resistance ($R_{\text{nose}}$) for inspiratory airflow of 250 ml/s through left and right cavities combined.

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>Temperature ($^\circ$C)</th>
<th>RH (%)</th>
<th>Water content (kg/m$^3$)</th>
<th>$R_{\text{nose}}$ (Pa/(ml/s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heathy nose 1</td>
<td>32.4</td>
<td>100.0</td>
<td>0.0366</td>
<td>0.070</td>
</tr>
<tr>
<td>Heathy nose 2</td>
<td>32.3</td>
<td>100.0</td>
<td>0.0362</td>
<td>0.082</td>
</tr>
<tr>
<td>Heathy nose 3</td>
<td>32.3</td>
<td>100.0</td>
<td>0.0363</td>
<td>0.039</td>
</tr>
<tr>
<td>Heathy nose 4</td>
<td>32.0</td>
<td>99.8</td>
<td>0.0356</td>
<td>0.046</td>
</tr>
<tr>
<td>Atrophic pre-op</td>
<td>29.7</td>
<td>95.7</td>
<td>0.0297</td>
<td>0.028</td>
</tr>
<tr>
<td>Atrophic post-op</td>
<td>30.9</td>
<td>98.2</td>
<td>0.0330</td>
<td>0.119</td>
</tr>
</tbody>
</table>

Atrophic pre-op and atrophic post-op refer, respectively, to the pre- and post-operative geometries of the atrophic nose. Mucosal temperature and RH were assumed to be 32.6$^\circ$C and 100%, respectively.
TABLE 3 – Total heat and water fluxes per unit area in each region of the nasal cavity.

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>HEAT FLUX (10^3 W/m^2)</th>
<th>WATER FLUX (10^-4 kg/s.m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LEFT</td>
<td>RIGHT</td>
</tr>
<tr>
<td>Heathy nose 1</td>
<td>1.12</td>
<td>0.93</td>
</tr>
<tr>
<td>Heathy nose 2</td>
<td>1.17</td>
<td>1.24</td>
</tr>
<tr>
<td>Heathy nose 3</td>
<td>0.66</td>
<td>1.05</td>
</tr>
<tr>
<td>Heathy nose 4</td>
<td>1.01</td>
<td>0.80</td>
</tr>
<tr>
<td>Atrophic pre-op</td>
<td>1.17</td>
<td>0.78</td>
</tr>
<tr>
<td>Atrophic post-op</td>
<td>2.18</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Atrophic pre-op and atrophic post-op refer, respectively, to the pre- and post-operative geometries of the atrophic nose. LEFT = Left cavity, RIGHT = Right cavity, NASOP. = Nasopharynx.
TABLE 4 – Flow partitioning between left and right nasal passages in the 6 human nasal geometries studied.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Flow Partitioning</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left Cavity</td>
<td>Right Cavity</td>
<td></td>
</tr>
<tr>
<td>Healthy nose 1</td>
<td>54.7%</td>
<td>45.3%</td>
<td></td>
</tr>
<tr>
<td>Healthy nose 2</td>
<td>48.1%</td>
<td>51.9%</td>
<td></td>
</tr>
<tr>
<td>Healthy nose 3</td>
<td>37.5%</td>
<td>62.5%</td>
<td></td>
</tr>
<tr>
<td>Healthy nose 4</td>
<td>57.6%</td>
<td>42.4%</td>
<td></td>
</tr>
<tr>
<td>Atrophic pre-op</td>
<td>63.8%</td>
<td>36.2%</td>
<td></td>
</tr>
<tr>
<td>Atrophic post-op</td>
<td>90.8%</td>
<td>9.2%</td>
<td></td>
</tr>
</tbody>
</table>

Atrophic pre-op and atrophic post-op refer, respectively, to the pre- and post-operative geometries of the atrophic nose.
FIGURE 1: Cross-sectional areas of coronal sections of the human nose (left and right cavities combined). The distance along the nose is measured from the first coronal section after the nostrils. The curve representing a normal nose is an average of the 4 healthy subjects included in this study; the bars show the range of variation in these data. Atrophic pre-op and atrophic post-op refer, respectively, to the atrophic nose before and after surgery.
FIGURE 2: Airflow patterns in the atrophic nose compared to a healthy nasal cavity colored by air speed magnitudes. LEFT: Streamlines of massless particles released from the left nostril. RIGHT: Airflow distribution at coronal cross-sections at (a) 15 mm, (b) 35 mm, and (c) 55 mm after the nostrils.
FIGURE 3: (a) Temperature and (b) water content of the air stream averaged over coronal cross-sections along the human nose. See the caption of Fig. 1 for more information on symbols.
FIGURE 3: (a) Temperature and (b) water content of the air stream averaged over coronal cross-sections along the human nose. See the caption of Fig. 1 for more information on symbols.
FIGURE 4: Regions of the nasal mucosa where the water flux per unit area exceeds $2 \times 10^{-4} \text{ kg/sm}^2$. Only the left cavity and the nasopharynx are shown. (Nostrils are to the left, nasopharynx to the right.) Note that the water flux was set to be zero at the nasal vestibule. Atrophic pre-op and atrophic post-op refer, respectively, to the pre- and post-operative geometries of the atrophic nose.
FIGURE 5: Circumferential averages of (a) heat flux and (b) water flux through the nasal wall as a function of the distance from the nostrils. For each subject, the data represent the nasal cavity with the higher air flow rate (Table 4). See the caption of Fig. 1 for more information on symbols.
FIGURE 5: Circumferential averages of (a) heat flux and (b) water flux through the nasal wall as a function of the distance from the nostrils. For each subject, the data represent the nasal cavity with the higher air flow rate (Table 4). See the caption of Fig. 1 for more information on symbols.
FIGURE 6: Circumferential averages of (a) heat flux and (b) water flux through the nasal wall as a function of the height from the nasal floor. For each subject, the data represent the nasal cavity with the higher air flow rate (Table 4). See the caption of Fig. 1 for more information on symbols.
FIGURE 6: Circumferential averages of (a) heat flux and (b) water flux through the nasal wall as a function of the height from the nasal floor. For each subject, the data represent the nasal cavity with the higher air flow rate (Table 4). See the caption of Fig. 1 for more information on symbols.
FIGURE 7: Pressure averaged over coronal cross-sections versus distance from nostrils in the atrophic and normal noses studied. See the caption of Fig. 1 for more information on symbols.