

A model of airflow in the nasal cavities: Implications for nasal air conditioning and epistaxis

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ABSTRACT

Background: A friction force is generated when moving air contacts the nasal walls, referred to as wall shear stress. This interaction facilitates heat and mass transfer between the mucosa and air, i.e., air-conditioning. The objective of this research was to study the distribution of wall shear stress within the nasal cavity to identify areas that contribute significantly to air-conditioning within the nasal cavity.

Methods: Three-dimensional computational models of the nasal airways of five healthy subjects (three male and two female subjects) were constructed from nasal CT scans. Numerical simulations of nasal airflow were conducted using the commercial computational fluid dynamics code Fluent 6 (Ansys, Inc., Canonsburg, PA). Wall shear stress was derived from the numerical simulation. Air-conditioning was simulated to confirm the relationship with wall shear stress.

Results: Nasal airflow simulations predicted high wall shear stress along the anterior aspect of the inferior turbinate, the anteroinferior aspect of the middle turbinate, and within Little's area.

Conclusion: The airflow simulations indicate that the inferior and middle turbinates and Little's area on the anterior nasal septum contribute significantly to nasal air-conditioning. The concentration of wall shear stress within Little's area indicates a desiccating and potentially traumatic effect of inhaled air that may explain the predilection for spontaneous epistaxis at this site.

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Key words: Airflow, computer simulation, epistaxis, fluid dynamics, human, humidification, nose, respiration, shear stress, turbinates

Fluids, including air, have a natural resistance to flow. This property is termed viscosity. When air flows over a surface the molecules adjacent to the surface become stationary in a time-averaged sense, a situation referred to as the “no slip” condition in aerodynamics. These molecules still possess thermal energy, which is expressed by vibration; this makes mixing with molecules further from the wall possible, and an exchange of momentum occurs in which momentum is transferred from the airstream to the stationary wall. A special region of flow develops between the main body of the airflow and the surface over which it passes, called the boundary layer. The friction force maintaining air in contact with the surface stationary is termed shear stress. The faster the adjacent molecules move the greater this force will be. Wall shear stress is therefore proportional to the velocity (or momentum) gradient of the air particles across the boundary layer.

The transfer of heat and moisture from a surface will depend on the concentration and temperature gradients between the warm, moist air immediately adjacent to the surface and the cooler, drier air in the main flow stream. The movement of water molecules between the surface and the airflow

is called mass transfer. Again, the velocity gradient across the boundary layer will be important for determining the concentration and temperature gradients because it will dictate how quickly heat and moisture dissipate across the boundary layer. This implies that velocity, heat, and mass transfer are all directly connected in the boundary layer and hence proportional to shear stress. This is referred to as the momentum, heat, and mass transfer analogy. The analogy is valid provided the mass transfer rate is small (a large diffusive vapor flow distorts the velocity, temperature, and concentration profiles in the vicinity of the surface) and wall shear stress (skin friction) is largely responsible for the momentum change.¹ Momentum change occurring because of vortex formation in the presence of an obstruction, called form drag, does not share this same relation with heat and mass transfer.^{1,2}

Directly measuring wall shear stress in a nose is not technically feasible. However, values of wall shear stress can be calculated in computer models of airflow through a nose using an engineering process called computational fluid dynamics (CFD). The ability to do this has previously been illustrated by the CFD study of one anatomically accurate nasal cavity.³ CFD can also be used to determine the air-conditioning characteristics of the human nose, although additional equations need to be solved. The aim of this investigation is to determine if shear stress can adequately predict areas that are potentially important for heat transfer and mass transport in the nose (nasal air-conditioning) and then to study shear stress patterns in a number of nasal cavities.

MATERIALS AND METHODS

After approval from the Local Research Ethics Committee, a coronal helical CT scan of the nasal airway was performed

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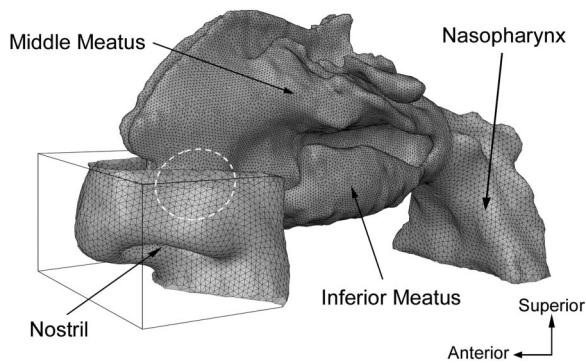


Figure 1. A typical three-dimensional computer model of the nasal airway. The inlet faces for airflow are placed on the box surrounding the anterior nares. The approximate location of Little's area is marked with a dashed line.

on five asymptomatic adults without prior nasal surgery. The slice width was 1–2 mm using a low radiation dose protocol.⁴ The CT data were converted into a three-dimensional computer-aided design (CAD) model of the nasal airway using the software package MIMICS 8.1 (Materialise, Leuven, Belgium). To facilitate the interaction of inspired air with the external nose and adjacent face, the CAD model included a block of air around these structures (Fig. 1). Each model thus contained the external nose, both nasal passages, and the nasopharynx.

The CAD model was converted into a tetrahedral volume mesh using ICEMCFD tetra 4.3.1 (Ansys, Inc., Canonsburg, PA). A grid-independence study was conducted to determine the optimal size for mesh elements. The meshes used contained ~850,000–1,100,000 tetrahedral elements and 180,000–225,000 nodal points, depending on the dimensions of the individual nasal cavity. To ensure mesh quality, all cells had an aspect ratio of >0.3 . Figure 2 is a dissection view of a mesh with the velocity magnitude of the airflow superimposed showing several layers of tetra mesh in the boundary layer; the slower airflow is colored blue. Numerical flow simulation of second-order accuracy was performed using FLUENT 6.1 (Ansys, Inc.). The CFD technique used was validated by comparison with empiric results obtained for an identical solid model.^{5,6} The flow was assumed to be laminar; this assumption is supported by our own experimental findings^{5,6} and those from Croce *et al.*⁷ and Zhao *et al.*⁸ A pressure inlet boundary condition was specified as atmospheric pressure (0 Pa gauge pressure) at the external nose and a constant, physiologically realistic negative pressure sufficient to produce a resting breathing flow rate was specified at the outlet face. The incompressible Navier-Stokes equations were solved using a cell-based, implicit, segregated method. Pressure-velocity coupling was achieved using the SIMPLEC algorithm. Inspiration was modeled as a steady flow through a rigid structure. To model air-conditioning the air and water vapor entering the nose was specified to have a specific heat capacity of $1005.9 \text{ J kg}^{-1} \text{ K}^{-1}$, a thermal conductivity of $0.0268 \text{ W m}^{-1} \text{ K}^{-1}$, a viscosity of $1.88\text{E}-05 \text{ kg m}^{-1} \text{ s}^{-1}$, a temperature of 298 K, a mass diffusivity of $2.6\text{E}-05 \text{ m}^2 \text{ s}^{-1}$, and a mass fraction of water of 0.004. The temperature of the nasal walls was set to a constant 310 K and the mass fraction of water in

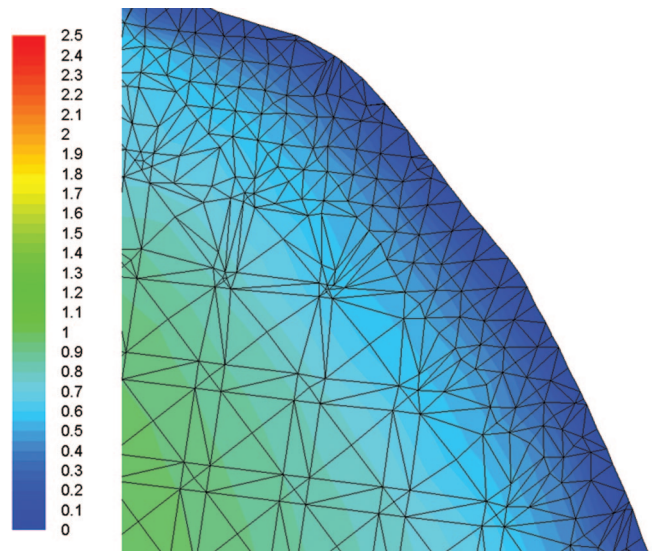


Figure 2. Several layers of denser tetrahedral cells capture the boundary layer.

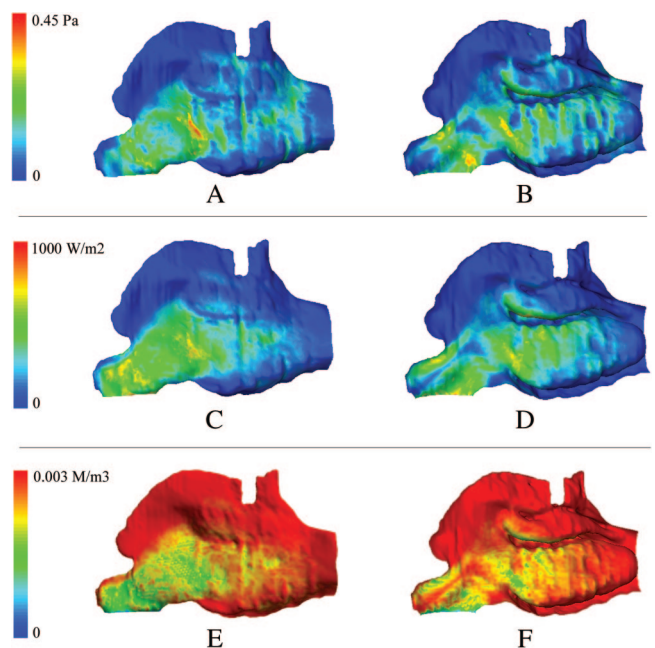


Figure 3. (A and B) Shear stress distribution, (C and D) surface heat transfer, and (E and F) molar concentration of water adjacent to the nasal wall in the right nasal cavity of patient A.

the adjacent air was set to 0.04. Mucosal thermal conductivity was $3558 \text{ W m}^{-1} \text{ K}^{-1}$. These values were obtained from a prior study.⁹

RESULTS

The relationship between wall shear stress and the air-conditioning capacity of the nose is depicted in Fig. 3. The results are derived from the modeling of airflow, heat, and mass transport in the right nasal cavity of patient A. The septal wall is portrayed in images shown in Fig. 3, A, C, and E and the lateral wall (viewed from within the nasal cavity) in

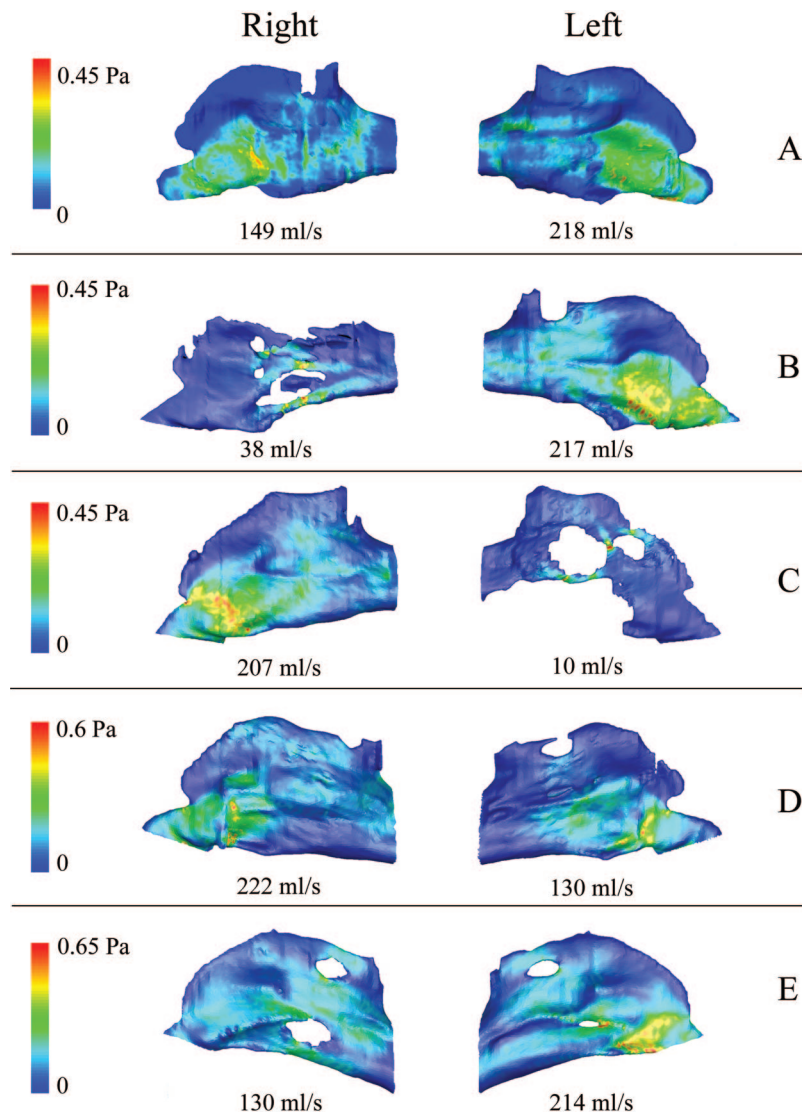


Figure 4. Wall shear stress distribution on the septal wall of the nasal cavity.

the remaining images. Images shown in Fig. 3, A and B, show shear stress ranging from 0 to 0.45 Pa, concentrated in Little's area of the septum shown in Fig. 3 A and at the lateral aspect of the ostium internum, along the inferior border of the middle turbinate, and the anterior half of the inferior turbinate shown in Fig. 3 B. Surface heat transfer ranges from 0 to 800 W/m² in Fig. 3, C and D. Again, heat transfer is concentrated in Little's area, the lateral wall of the vestibule, the inferior border of the middle turbinate, and the anterior half of the inferior turbinate. The relationship with shear stress varies in magnitude at exact locations, but within regions of the nasal cavity there is good similarity. In images shown in Fig. 3, E and F, the molar concentration of water in the flow adjacent to the nasal wall is depicted. The airflow simulation assumes that the nasal mucosa has an unlimited ability to supply moisture at resting conditions and, therefore, decreases in water concentration within the airflow adjacent to the surface indicates areas from which the greatest amount of water is being removed. The anterior half of the septal wall in Fig. 3 E and the lateral aspect of the ostium internum, inferior border

of the middle turbinate, and anterior half of the inferior turbinate in Fig 3 F are such areas. Again, there is broad similarity with shear stress distribution but with minor variations in the relationship at exact positions. This similarity was also apparent in the other nasal cavities studied; the heat transfer and molar concentration plots of the right nasal cavity of patient A only are presented to establish this overall similarity.

CFD predictions of wall shear stress within each side of the other nasal cavities studied are depicted in Figs. 4 (septal wall) and 5 (lateral wall). The maximal values of shear stress predicted for each nasal cavity ranged from 0.39 to 0.65 Pa. The average shear stress for each nasal cavity ranged from 0.02 to 0.08 Pa. The predicted airflow rate through each nasal cavity is included to indicate how the anatomic conformation of each nose partitioned the airflow between the two nasal cavities.

All of the nasal cavities studied showed some degree of asymmetry in the congestion of the right and left nasal mucosa, particularly with patients B and C. Contact between the

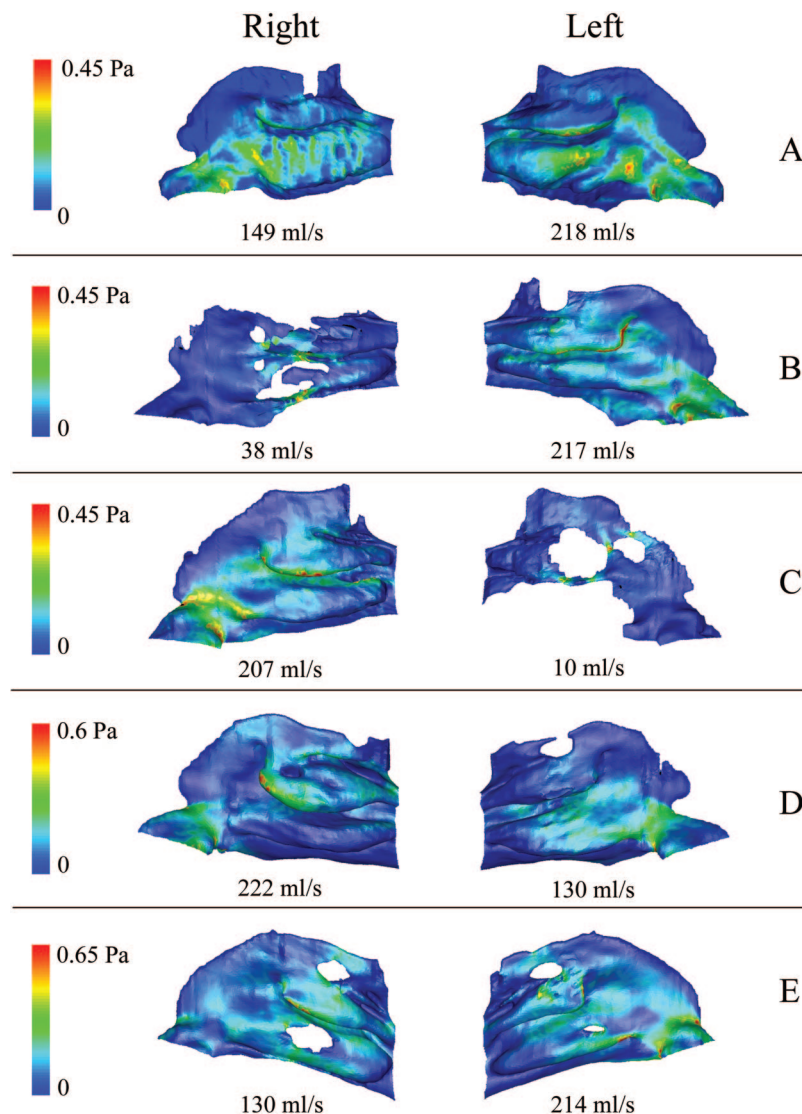


Figure 5. Wall shear stress distribution on the lateral wall of the nasal cavity.

medial and lateral walls on the congested side is responsible for the white areas within these nasal cavities in Figs. 4 and 5. In addition, the nasal septum was deviated in patients D and E.

Seven of ten nasal cavities in Fig. 4 have high levels of shear stress in Little's area. In the two nasal cavities showing considerable mucosal congestion (right side of patient B and left side of patient C), wall shear stress values are generally low as a consequence of the very low flow rate, with several small areas of isolated high wall shear stress in the regions of minimal cross-sectional area (0.41 and 0.45 Pa, respectively). Shear stress levels were also predicted to be low (maximum of 0.17 Pa) in the right Little's area of patient E, where a septal deviation to the opposite side has resulted in a concavity in this region. Patient-specific differences were apparent in both maximal wall shear stress values predicted within Little's area and the pattern of distribution of wall shear stress. The highest values of wall shear stress predicted in this study occurred in the nasal cavities with septal deviations (patients D and E

in Fig. 2) on the side of the deviation (0.60 and 0.65 Pa, respectively).

Wall shear stress plots for the lateral wall of the nasal cavities predict high friction in the region of the lateral aspect of the ostium internum, anterior aspect of the inferior turbinate, and anteroinferior aspect of the middle turbinate for 7 of 10 nasal cavities (up to 0.56 Pa). The wider (right) side of nasal cavity E does not show high wall shear stress at the lateral aspect of the ostium internum.

Increasing the flow rate increases the magnitude of the shear stress but does not alter its distribution. This is shown in Fig. 6 where Fig. 6, A and B, show shear stress through the right nostril of patient A at a doubled flow rate. Fig. 6, C and D, shows the effect of reversing the airflow through the same nasal cavity. Shear stress is much more evenly distributed through the nasal cavity with decreased peak values. Elevated shear stress can still be seen at the anterior end of the septal wall, at the ostium internum on the lateral wall, and on the posterior face of the nasal sill on the floor of the nose.

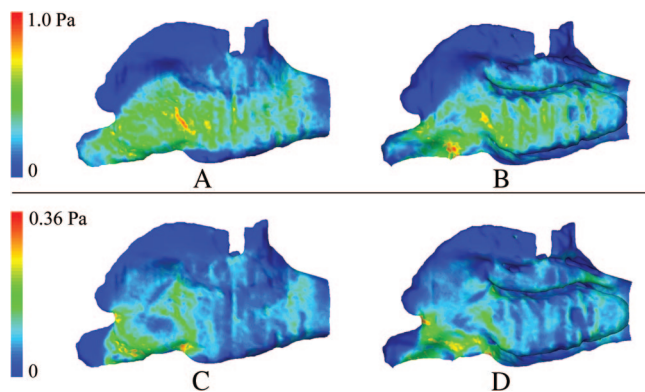


Figure 6. Wall shear stress distribution in the right nasal cavity of patient A at (A and B) increased airflow and with (C and D) reversed airflow.

DISCUSSION

The momentum boundary layer is not the only influence on heat and mass transport from an adjacent surface. The nature and behavior of the main flow will also have an effect on concentration gradients, especially when air enters an enclosed space where it may become saturated before exiting. Even though the relationship between wall shear stress and heat and mass transfer has been shown to be applicable to a wide range of conditions,¹⁰ including pressure gradients applicable in nasal airflow, it was necessary to perform direct heat and mass transport simulations in the nasal cavities. The results, an example of which is shown for the right side of patient A, indicate broad similarity for the distributions of shear stress, heat transfer, and molar concentration of water (indicating important areas for humidification) with slight variation in the magnitude of the relationship at precise locations. The simpler process of numerically modeling shear stress is therefore appropriate for defining areas important for air-conditioning within the nasal cavities. It should be clarified that conductive and convective heating were modeled but not radiation or evaporative cooling. The latter would seem to have a negligible contribution: correlation between *in vivo* temperature measurements and CFD predictions based on conductive and convective modeling have previously been reported.¹¹

Levels of shear stress are subject to temporal variations during the breathing cycle.³ Likewise, absolute values of local temperature and velocity are dependent on the precise location and time of detection.¹² However, most of inspiration is dominated by a steady-state inflow of air and the general pattern of temperature and velocity distribution has been shown to be similar throughout the breathing cycle.¹² Shear stresses calculated during steady-state conditions, as in this study, are therefore indicative of typical inspiration levels. Unfortunately, it is not technically feasible to measure wall shear stress in either live noses or physical models of the nose. Our previously published finding that the velocity distribution calculations were correct when the computer model of one of the geometries was compared with experimental results obtained from a corresponding physical model⁶ enhances confidence that the shear stress calculations are correct.

The observation of relatively high shear stress along the anterior aspect of the inferior turbinate and anterior and inferior aspects of the middle turbinate is not surprising, given that these structures have previously been reported to be important in nasal air-conditioning.^{13,14} High shear stress on the septum, turbinates, and middle meatus was found in the previous study of one anatomically accurate nasal cavity, although the greater number of anatomically accurate nasal cavities in this study indicates that the nasal septum is more frequently the target of higher shear stress than the middle meatus. Little's area, in particular, on the anteroinferior nasal septum typically featured 10 times the average shear stress predicted for the nasal cavity in this study. The air-conditioning role of Little's area is further supported by histological examination of the vessels within Kiesselbach's plexus that show specializations in keeping with fluid secretion.¹⁵ This plexus would therefore moisten and heat the mucosa of Little's area protecting it from excessive cooling and drying as it warms and humidifies inspired air. It has previously been reported that nasal humidity is reduced in patients with an anterior septal perforation.¹⁴ Nasal air temperature was not significantly reduced though, suggesting that the nose is still able to adequately heat inspired air without contribution from Little's area.

Wall shear stress is not an entirely benign facilitator of nasal function. In an animal study of the nasal mucosa in rabbits after occluding one nasal passage, the increased airflow (and hence increased velocity gradients and shear stress) on the patent side of the septum damaged the ciliated cells and caused vascular dilatation at a site 10 mm from the cutaneous border. More posteriorly on the septum there was no change.¹⁶

There is a predilection for spontaneous epistaxis to occur in Little's area. Although we do not propose that shear stress is the underlying cause of epistaxis, we do suggest that it is the mechanism by which certain sites are predisposed to epistaxis. In the case of Little's area, the cooling, drying, and traumatic effects of the wall shear stress exceeding the protective warming and moistening properties of Kiesselbach's plexus would promote epistaxis. It is often reported that epistaxis rates are higher on cool, dry days.¹⁷ Crusting of secretions in this area caused by excessive drying can provide an impetus to nose picking, which may also damage mucosa or alternatively mucosa damaged by nose picking will be subject to the adverse effects of shear stress. The role of shear stress may also explain why antiseptic carrier cream is effective in treating anterior epistaxis,^{18–20} as the layer of cream over Little's area may serve to protect this area from shear stress permitting mucosal healing.

Although the number of nasal cavities investigated in this study is small, the overall consistency of the prediction of high friction in Little's area suggests that these findings are not random. Individual variation in both the maximal shear stress value predicted and the pattern of distribution in this study may be one reason why certain individuals are more prone to epistaxis.

CONCLUSIONS

The pattern of wall shear stress predicted by CFD within the nasal cavities studied indicates that the inferior turbinates,

middle turbinates, and Little's area (anteroinferior nasal septum) are important areas for nasal air-conditioning. High wall shear stress within Little's area may also explain the predilection of spontaneous anterior epistaxis for this site. The magnitude and distribution of wall shear stress within a nasal cavity relates to its geometrical conformation and the maximum value predicted occurred on the side of a nasal septal deviation. This may explain why certain patients seem prone to recurrent epistaxis and the finding that patients with recurrent epistaxis in conjunction with a nasal septal deviation often bleed from the side of the deviation.

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