Finite Element Analysis of Airflow in the Nasal Valve

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- We digitized the outline of the nasal cavity from images obtained after applying contrast material to the nose. A computer-aided simulation of flow was undertaken in the sagittal plane in the anterior nasal cavity. Previous work on the nasal valve was reviewed. Our results showed that the nasal valve is an oblique structure bounded laterally by the caudal end of the upper lateral cartilage, medially by the septum, and ventrally by the inferior rim of the piriform aperture. We found that this rim, projecting from the floor of the nose, produces an uneven distribution of airflow through the valve with most of the flow occurring in the ventral segment. Removal of this rim should result in a more even distribution of flow across the valve. (Arch Otolaryngol Head Neck Surg. 1993;119:638-642)

This effort represents an attempt at understanding the pattern of flow in the nasal valve using a computer-aided mathematical simulation of airflow in the nasal valve. A review of previous investigators' work on the anatomy, function, and dysfunction of the nasal valve is necessary to convey our understanding of the different terms used and to try to establish a clearer definition of these terms.

DEFINITION OF THE NASAL VALVE

Mink1 was the first to use the term "nasal valve" asserting that this segment with its most anterior edge, the ostium internum, plays a critical role in nasal respiration. This initial clear anatomic definition was later replaced by a functional concept of the nasal valve representing the narrowest segment (and therefore the area with the highest resistance) as stated by Van DISHOECK2 in 1957: "The resistance of an airstream in a short pipe of changing diameter such as the nose is mainly determined by the narrowest spot."

The location of the narrowest segment in the nasal passages has been a controversial topic in the literature and will be discussed under anatomy of the nasal valve. A more meaningful definition was brought about by the work of Bridger and PROCTOR2 on the upper lateral cartilage area acting as a collapsible "flow-limiting segment." We believe that the last two functional definitions apply to the same anatomic area as will be discussed.

ANATOMY OF THE NASAL VALVE

The location of the nasal valve has been a subject of wide controversy in the literature. Early investigators (Van DISHOECK1 and MINK) used direct observation and anatomic dissection to define the narrowest segment of the nasal cavity. Bachmann and Legler3 studied the anterior nasal cavity using luminal impressions and concluded that the narrowest segment is a well-defined ostium bounded laterally by the limen nasi, medially by the septum, and inferiorly by the rim of the piriform aperture. Their major contribution was to stress the fact that the nasal valve is perpendicular to the nasal septum, departing from the more traditional concept of the medial border of the nasal valve lying more anteriorly at the cutaneous-mucosal junction (Fig 1).

In a more recent report, Grymer6 described the use of acoustic rhinometry to locate the minimal cross-sectional area at the anterior end of the inferior turbinate and reported its shift more anteriorly to the ostium internum in the decongested nose. The basic understanding inherent in the investigative methods just mentioned is that the main site of nasal resistance is synonymous with the narrowest segment in the nasal passages. Such an assumption, while true in simple structures, is unapplicable in the more complex ones (such as the nose) where the pattern of flow plays a significant role in the distribution of resistance along the passage. Therefore, a more direct approach to the question by measuring pressure changes and calculating resistance should be adopted.

Haight and Cole7 passed a small transducer along the floor of the nasal cavity and located the largest decline in pressure (and thus the major resistive segment) at the area of the inferior rim of the piriform aperture and concluded that "the anterior bony cavity is the main site of nasal resistance" (Fig 2). This conclusion was based on a theoretical reproduction of the plane of maximum resistance from a one-point measurement. We believe it would be more aerodynamically sound to reproduce that plane in a perpendicular fashion to the airflow rather than the wall of the cavity as illustrated in Fig 3. We obtained lateral roentgenograms of the skull after application of contrast material to the walls of the nasal cavity anteriorly in two healthy volunteers. The caudal ends of the upper lateral cartilage were tagged externally using metal markers. The plane of max-

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Fig 1.—A mold of the right nasal cavity as viewed from above. Arrows indicate the site of the valve and the solid white line indicates the traditional concept of ostium internum.

Fig 2.—Haight and Cole findings. (From Haight and Cole.7)

Fig 3.—Top, The plane as reproduced by Haight and Cole.7 Bottom, A more aerodynamically accurate reproduction of the plane. (From Haight and Cole.7)

FUNCTION OF THE NASAL VALVE

Bridger and Proctor3 described the presence of a collapsible flow-limiting segment correlating to the upper lateral cartilage. When the negative nasopharyngeal and intranasal pressure is increased to generate more flow, it produces a proportional increase in the transmural pressure gradient (normal atmospheric pressure minus intranasal pressure) until the latter reaches a critical value triggering off the collapse of the upper lateral cartilage as illustrated in Fig 5. This valve mechanism would limit the amount of flow that could be generated in the nasal cavity. One could hypothesize that once the functional capacity of the nose to provide filtration, humidification, and temperature regulation is exceeded by the amount of airflow, this flow-limiting mechanism steps in to diverge the
flow into the oral cavity thereby saving the organism the extra energy required for nasal respiration. It is essential to recognize that there are only two variables controlling valve closure: (1) the amount of negative pressure generated at the site, and (2) the critical transmural pressure gradient, a function of the mechanical properties of cartilage and soft tissue. The role of alar muscles is controversial in normal breathing. It has been shown that facial paralysis will result in premature valve collapse and altered flow-pressure relationship. \(^1,7,9\) Whether this effect is secondary to a loss of neural rhythmic discharge to these muscles or atrophy and loss of tonicity is unknown. However, active flaring of the nostril has been shown capable of altering the patency and resiliency of the valve and therefore preventing its collapse. \(^9\)

**DYSFUNCTION OF THE NASAL VALVE**

Any pathologic closure of the nasal valve under normal *nonstressful* conditions would therefore result from either (1) a lower critical transmural pressure gradient (a function of the mechanical properties of the soft tissues) or (2) an increase in the amount of negative pressure generated at the valve site needed to generate normal flow. Clinically, flaccid nasal walls would represent a change in the mechanical properties of the soft tissues and cartilages and would result in a lower critical transmural pressure. Any nasal obstruction at the valve site or anterior to it would result in more negative pressure generated at the valve and would therefore produce a closure as illustrated in Fig 6. Valve closure under *stressful* conditions is a normal physiologic response.

**APPROACH TO MANAGEMENT**

To prevent a pathologic closure, one could manipulate either one of the two variables controlling the valve mechanism. Stabilization of the upper lateral is aimed at changing the mechanical properties of the valve wall and therefore producing a higher critical transmural pressure. The alternative approach is to increase the size of the airway at

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*Fig 4.—The location of the valve when the plane was reproduced over lateral roentgenograms as indicated in the text.*

*Fig 5.—The mechanism of the valve closure.*

*Fig 6.—An obstruction anterior to the valve site will produce more negative pressure at the valve and therefore a closure (for illustrative purposes only).*

*Fig 7.—The two models used: model 1 with the inferior rim of the piriform aperture and model 2 after the rim was removed.*
Fig 8.—The computational grid used in both models.

Fig 9.—The streamline contour plots. Note that most of the flow in model 1 occurs in the ventral part of the valve. Note the more even distribution of flow in model 2 with more flow occurring in the dorsal segment of the valve.

Fig 10.—Velocity vector plots; the same findings as indicated in Fig 9 are noted.
the valve or anterior to it and thereby reducing the amount of negative pressure generated at the valve.

INTRODUCTION INTO FINITE ELEMENT METHODS

Finite element analysis of flow is a computer-aided mathematical simulation of airflow heavily used by the aircraft manufacturing industry. Simply stated, it divides the structure in question into multiple small subdivisions and then employs basic equations in physics to simulate flow in that structure. The advantages of finite element analysis over the more traditional flow visualization studies are many, but these methods are basically complementary. Finite element allows for "an understanding" of flow and the effects of certain areas in the geometry of the structure on the flow. The fact that the data obtained cover every point in the structure is another advantage over other methods where only representative sampling is possible. Again, one has to stress that these methods are complementary and that they all serve specific ends.

METHODS

The contour of the anterior nasal cavity was reproduced from lateral skull roentgenograms after applying a thin film of contrast material to the anterior part of the nose in two healthy white volunteers. The images obtained were then digitized independently using a three-dimensional design aid. A representative model of a sagittal section of the anterior nasal cavity was obtained (model 1, Fig 7). Another model was obtained by removal of the inferior rim of the piriform aperture (model 2, Fig 7). These two models served as the geometry from which a computational grid was constructed (Fig 8). For this computation, a software package (Fluid Dynamics International, Evanston, III) was used. The simulation was undertaken in both models with entry and exit conditions comparable to the ones physiologically occurring in the nasal cavity. Results were obtained as streamline contour plots and velocity vector plots, and the simulation and conclusions were limited to the anterior nasal cavity and the valve area where the anatomy was carefully reproduced and did not include the exit and entry segments.

RESULTS

The results and the conclusions were limited to the very anterior of the nasal cavity. Analysis of the streamline contour plots and the velocity vector plots shown in Figs 9 and 10 could be summarized in the following five statements. (1) Most of the flow occurs at the ventral part of the valve close to the inferior rim of the piriform aperture. (2) The dorsal valve area acts as dead space with minimum flow occurring in that area. (3) The inferior rim of the piriform aperture is the one important factor in the geometry of the anterior nasal cavity that produces the pattern of flow described in the previous two statements. (4) Removal of the inferior rim of the piriform aperture produces a more even distribution of flow across the valve with more flow directed toward the dorsal part of the valve. (5) Under the same entry and exit conditions, removal of the inferior rim of the piriform aperture would result in a significant increase in flow depending on the set of conditions in consideration.

COMMENT

The main theme being stressed in this article is the concept of the nasal valve as a clearly defined structure with a rather complicated pattern of airflow. We did not make any comments on the airflow pattern in the mid and posterior parts of the nasal cavity since there are other very important variables in the coronal plane affecting flow through that segment. Our results (namely, that most of the airflow occurs through the ventral part of the valve) could be supported by the fact that in the coronal plane, the nasal valve assumes an almost triangular shape with the base being ventral and therefore allowing for more flow ventrally. Although this study indicates that removing the inferior rim of the piriform aperture when dealing with valve collapse "makes sense," the effectiveness and feasibility of this approach remains to be evaluated by a clinical study. The absence of this rim projecting from the floor of the nose in blacks could be one reason why there is a racially different flow-pressure relationship with significantly more flow required to produce a valve closure. However, there are other anatomic factors that could account for these differences.

CONCLUSIONS

The nasal valve is a well-defined structure, lying obliquely in the sagittal plane and bounded laterally by the caudal end of the upper lateral cartilage, medially by the septum, and ventrally by the inferior rim of the piriform aperture. It is perpendicular to the septum and its medial edge is posterior to the septal mucocutaneous junction.

Most of the flow occurs through the ventral part of the valve in proximity to the inferior rim of the piriform aperture. The inferior rim of the piriform aperture is a critical component in the geometry of the valve distorting airflow through it and resulting in the above-mentioned pattern of flow. Removal of this rim should result in a more even distribution of flow across the valve.

References

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