The effect of "Pyriform Turbinoplasty" on nasal airflow using a virtual model*

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Abstract

Background: A new procedure, pyriform turbinoplasty, is described and nasal airflow is measured before and after this procedure in a virtual model.

Methodology: Pyriform turbinoplasty is the submucosal reduction of the bone of the frontal process of the maxilla and the lacrimal bone. It opens part of the lateral margin of the nasal valve area with minimal damage to nasal mucosa. The resection of bone in this area can be extended by "nasal wall lateralization" when the lacrimal bone that joins the uncinate process behind the lacrimal duct as well as the base of the inferior turbinate and the edge of the maxilla at the rim of the pyriform aperture are removed. Nasal airflow was simulated using computational fluid dynamics and ANSYS Fluent solver.

Results: Analysis using fluid dynamics showed that these procedures help ventilation in the main airflow areas without substantially altering the normal pattern of airflow.

Conclusions: The changes after performing a pyriform turbinoplasty seem to be an improvement when compared to the changes after inferior turbinate surgery that can misdirect the airflow largely through the inferior meatus.

Key words: turbinate surgery, pyriform turbinoplasty, nasal wall lateralization, nasal airflow, numerical simulation, nasal valve area, computational fluid dynamics, ANSYS fluent solver

Introduction

Nasal obstruction can significantly impair patients' quality of life [1,2]. Inferior turbinate hypertrophy is the commonest cause of the sensation of nasal airway obstruction and it is most frequently due to allergic, non-allergic rhinitis and rhinosinusitis [3,4]. The majority of patients can be helped by medical treatment but when this does not work surgical procedures on the inferior turbinate (partial and total turbinectomy, turbinoplasty techniques, electrocautery, laser cautery and newer techniques that include radiofrequency, microdebrider submucous reduction and ultrasound turbinate reduction) are an option. Short-term improvement after procedures on the inferior turbinate have been reported [5,6] but the long-term benefit of these procedures is frequently poor as the mucosa re-hypertrophies [7]. There is no consensus at present as to which surgical technique is most effective and has least morbidity for the patient [8,9]. The influence of the inferior turbinate on nasal airflow and resistance is intricately associated with the nasal valve area, the narrowest conduit of airflow in the nose. The nasal valve area comprises the septum medially and the tuberculum of Zukercandle, superiorly and laterally the caudal margin of the upper lateral cartilages and the fibrofatty tissue over the pyriform aperture, the end of

Glossary: CFD: computational fluid dynamics; CT: computed tomography / CAT scan; IT: inferior turbinate; MT: middle turbinate; mm: millimetre; cm: centimetre; s: second the inferior turbinate and inferiorly, the floor of the pyriform aperture [10]. The correct terminology describes the internal nasal valve not as the cross sectional area but the angle of the specific slit-like segment between the caudal margin of the upper lateral cartilage and the septum, which is normally between 10 and 15 degrees [11]. The diagnosis and treatment of nasal valve dysfunction requires a thorough understanding of normal anatomy and function as well as pathophysiology of common abnormalities to properly treat the exact source of dysfunction [12]. There are primary causes of a narrow nasal valve area and these are relatively uncommon. They comprise a prolapse of the returning or end of the upper lateral cartilage into the nasal airway, lax or concave upper and/or lower lateral cartilages or a lack of overlap between them, and a narrow pyriform aperture. Secondary causes which effect the nasal valve area are more common and include turbinate hypertrophy, septal deviation, over-resection of the caudal border of the lower lateral cartilages, scar tissue in this area and a minor influence can result from weakness of the levator labii superioris alaeque nasi muscle. It is worth noting that a dry lining to the nasal mucosa can produce the sensation of a reduced airflow and this is easily missed as a cause of subjective nasal obstruction. This can be the result of surgery on the inferior turbinate and if not recognised can lead to further unnecessary and counterproductive turbinate surgery. The inferior turbinate is part of the internal nasal valve area where it plays a key role in nasal airflow and resistance as well as being important in the humidification and warming of ambient air towards the lungs so that any surgery on it should be done reluctantly, if at all. After airflow passes the anterior end of the inferior turbinate it travels to the middle meatus over the "shoulder" of the inferior turbinate just overlying the lacrimal system at the lateral edge of the pyriform aperture and this margin of the internal nasal valve also plays a key role in airflow [13]. For these reasons we propose a new endoscopic surgical technique to improve nasal airflow, the "pyriform turbinoplasy", with or without lateral nasal wall lateralization. Pyriform turbinoplasy is directed at the bone and produces a change of the architecture without removing any of the mucosa of the inferior turbinate. It comprises submucosal resection of the frontal process of the maxilla and part of the lacrimal bone (Figure 1). Nasal wall lateralization extends this concept to the submucosal resection of the frontal process of the maxilla and part of the lacrimal bone in conjunction with removal of the bony base of the inferior turbinate as it attaches to the maxilla (Figure 2A and B).

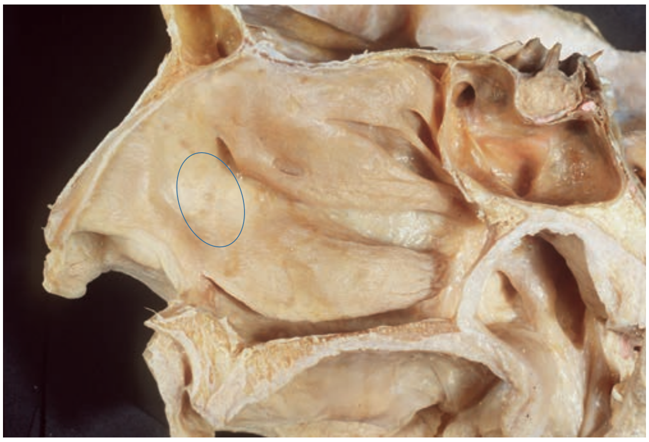

Figure 1. Specimen showing the area where submucosal dissection of the "shoulder" of the inferior turbinate is done.

Materials and methods

Based on the digital data from the CT-scanning of a patient with nasal obstruction and hypertrophy of the inferior turbinates, a

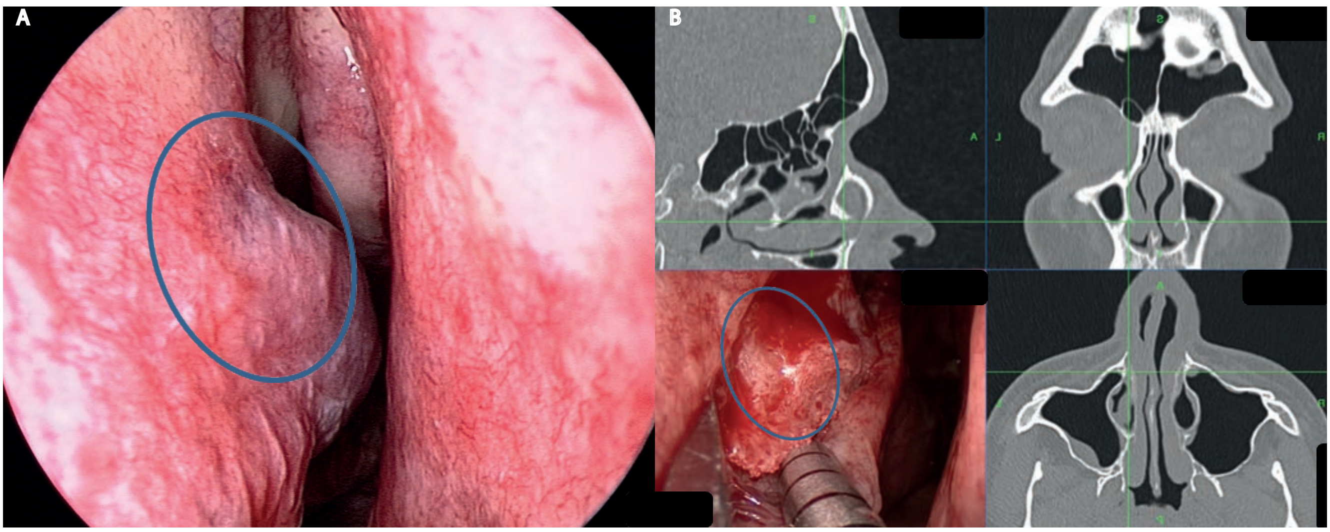

Figure 2. A) Narrowing of the right nasal airway caused by infringement of the "shoulder" of the inferior turbinate. B) Peroperative image guided view showing the position of the "shoulder" in three dimensions, left side.

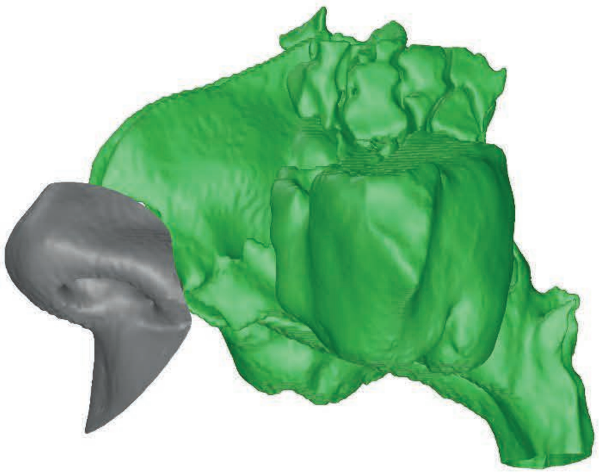

Figure 3. Three dimensional view of the virtual nasal model. Green coloured: nasal cavity, ethmoidal and maxillary sinus. Grey coloured: nasal entrance.

three dimensional computational model of the nasal cavity and paranasal sinuses was constructed. Patterns of air distribution within the nasal cavity and the middle meatus were simulated in this virtual model and the physics of fluid flow were analysed. The CT-Scan was performed on a GE Medical Systems Discovery 690 Scanner with an axial slice thickness of 0.63 mm. Segmentation was performed using the software ITKSnap V. 3.0.0. A tetrahedral mesh with 3.1 million cells was constructed around the model (Figure 3) with ANSYS (Workbench 14). The sphenoid and frontal sinuses were not included in the models as these

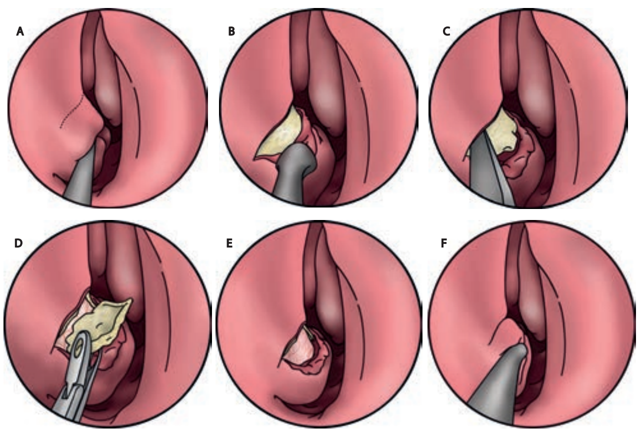

Figure 4. Diagrammatic representation of a pyriform-turbinoplasty. A) To define where the incision should be made the inferior turbinate is lateralized as much as possible and this reveals the "shoulder" which is to firm to outfracture. B) the incision is made high on the inferior turbinate. C) An osteotome is used to free the "shoulder". D) The bone is removed. E) The lacrimal duct can be seen when the bone has been removed. F) The mucoasl flap is replaced.

are not involved in the main airflow in the human nose. The numerical simulation was performed by the Computational fluid dynamics and ANSYS Fluent solver (ANSYS Workbench 14). The applied boundary conditions were based on known in vivo measurements [14-19]. In contrast to many other studies a transient simulation was performed. This was done by using in vivo results of intranasal pressure and inspired volume obtained from quiet breathing cycles. Inspired air was simulated at a temperature of 20°C and 30% relative humidity. Expired air was simulated at a temperature of 37°C and 100% relative humidity. This sequence was assumed with inspiration taking 2 seconds and expiration 2.2 seconds. One complete cycle had a duration of 4.2 seconds.

Pyriform turbinoplasty

Whilst the middle and posterior part of the inferior turbinate can be lateralized with ease, it is often difficult to do this with its anterior third and particular the "shoulder", which comprises the frontal process of the maxilla and part of the lacrimal bone. A horizontal incision is made over the base of the inferior turbinate where its "shoulder" is positioned (Figure 4A-F, Figure 5A-D). A broad flap is raised inferiorly and superiorly to expose the root of the inferior turbinate bone as it attaches to the lateral wall. An osteotome is placed at the base of the nub of bone that makes up the "shoulder" that intrudes into the nasal valve area. Only a gentle tap is needed to mobilize this fragment of bone before it is dissected free and removed. The lacrimal duct lies just behind this segment of bone so it is important not to damage this. The mucosa can then be replaced (Fig. 6A-E).

Nasal wall lateralization

Following a pyriform turbinoplasty, the lacrimal duct is identified and dissected laterally to expose where the lacrimal bone

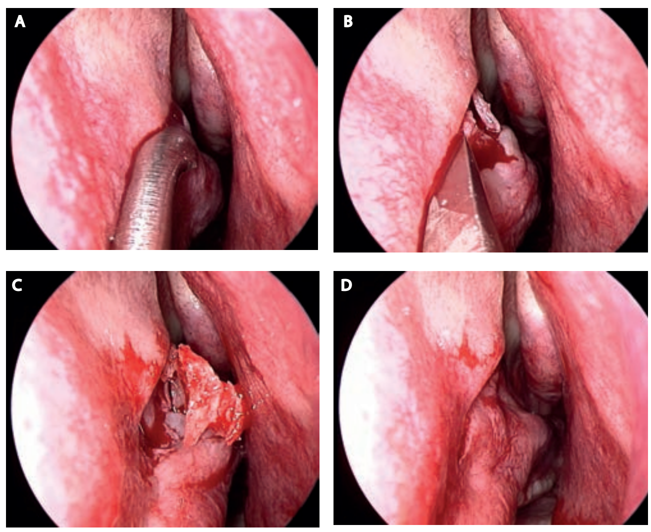

Figure 5. A) – D) Clinical pictures mirroring the procedure outlined in Figure 4A - F.

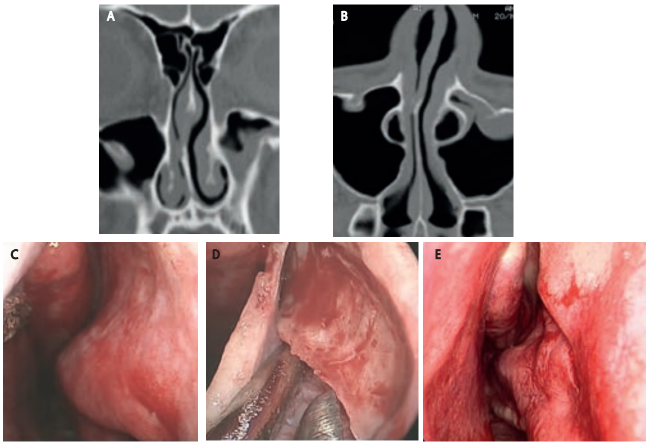

Figure 6. Pre-operative coronal (A) and axial (B) CT showing impingement of the left lateral nasal wall on the airway as well as septal deviation to the right and pre (C), peri- (D) and post- (E) operative view after piriform-turbinoplasty.

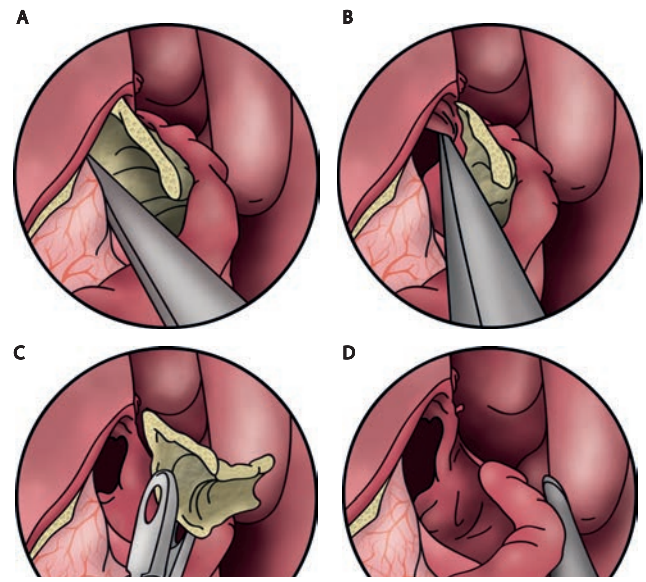

Figure 7. Nasal wall lateralization. A) The lacrimal duct is retracted laterally within its fossa. B) An osteotome fractures the segment of bone posterior and medial to the lacrimal system. C) The bone is removed – don't pull on it unless it is dissected free. D) The mucosa can be replaced.

attaches onto the maxilla. The bone that is exposed posterior, lateral and inferior to the lacrimal duct is then freed using an osteotome. Care should be taken not to twist the segment of bone towards the orbit as it is possible to tear the periorbita if there is a sharp spicule of bone (Figure 7A-D, Figure 8A-D). This bone comprises the junction of the lacrimal bone with the uncinate process behind the lacrimal duct, the base of the inferior turbinate and the edge of the maxilla at the pyriform aperture. Removal of this results in a more substantial widening of the lateral nasal wall (Figure 9 A,B).

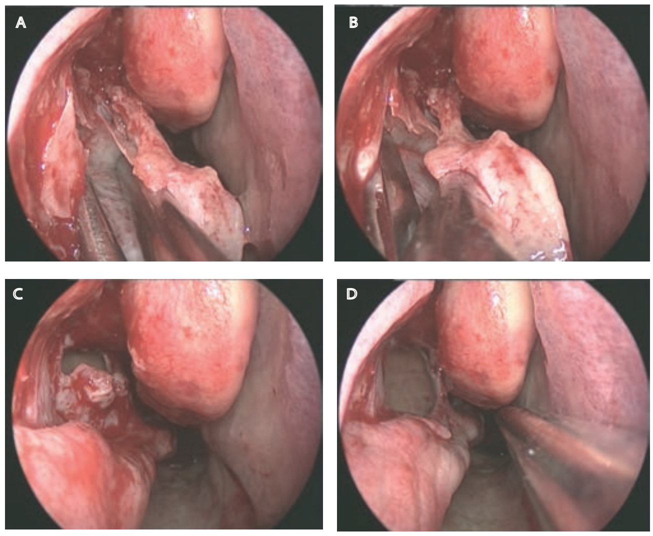

Figure 8 A-D). Clinical pictures mirroring the procedure outlined in Figure 7A-F (nasal wall lateralization).

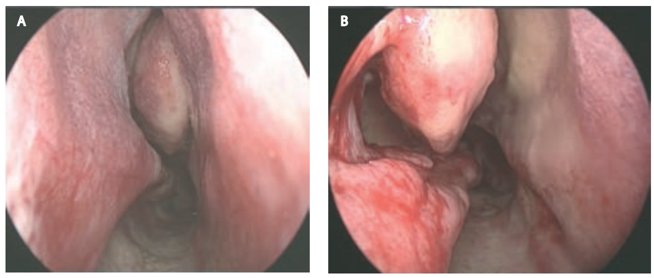

Figure 9. Pre- (A) and post- (B) operative view after nasal wall lateralisation in a revision case which had previously had an inferior turbinectomy.

Pyriform turbinoplasty and nasal wall lateralization can be done in conjunction with an extended maxillary sinusotomy as this enables the bone to be removed in this area without damaging the lacrimal duct.

Results

The highest velocity of inspired air was observed in the nasal valve area and this appears to act as a diffuser and distribute the airflow over the posterior areas of the nasal airway. The head of the inferior turbinate is, as a part of the nasal valve area, an essential element that helps this dispersion. Velocity in this area reaches up to 2.5 m/s during quiet respiration (Figure 10). In the coronal plane the airflow reaches up to 1 m/s next to the middle and inferior turbinate (Figure 11).

After performing an inferior turbinoplasty, the distance between the septum and inferior turbinate is enlarged by approximately 2 mm. In addition to the effect of reducing the shoulder of the inferior turbinate, this also leads to a significantly widened entrance to the middle meatus (Figure 12A,B). Simultaneous resection of the uncinate process, lateralization of the inferior

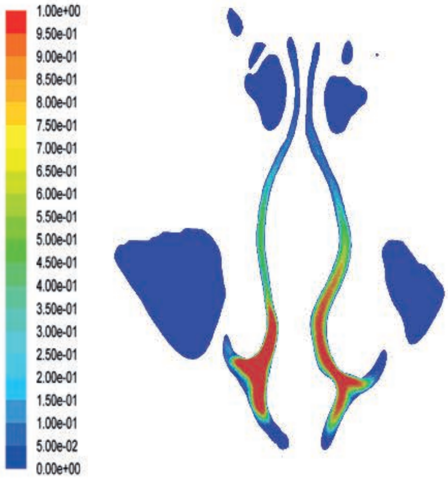

Figure 10. Coronal plane of the nasal model. Profiles of velocity magnitude [m/s] during inspiration immediately behind the nasal valve area. The main airflow takes place in the lower parts of the nasal cavity (red colour).

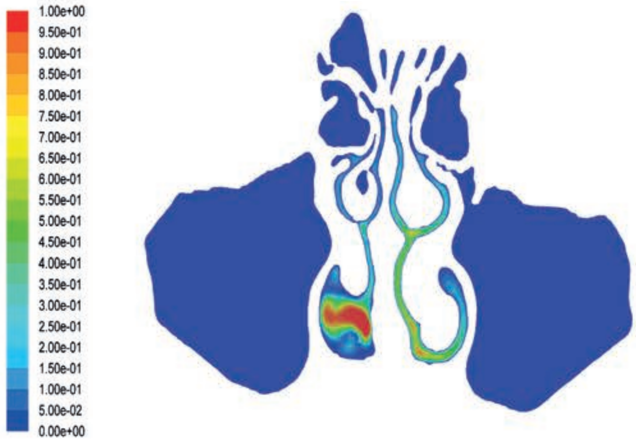

Figure 11. Coronal plane of the nasal model. Profiles of velocity magnitude [m/s] during inspiration around the middle and inferior turbinate as well as in the middle meatus. The airflow reaches up to 1 m/s next to the middle and inferior turbinate. The left side of the patient features a more consistent airflow. The airflow on the right side is focused on the area below the rest of the inferior turbinate (pipe-like airflow).

turbinate and the lateral nasal wall lead to an even greater widening of the passage lateral to the middle turbinate and both the inferior and middle meatus have an increase in airflow through a larger conduit and as a result improved and airflow with lower airspeeds (0.3 m/s preoperatively vs. 0.1 m/s postoperatively). This facilitates ventilation in the main flow areas without substantially altering the normal pattern of airflow. Compared to the preoperative conditions, the airspeed is generally reduced due to the increase in cross sectional area. The distribution of airflow in the posterior nasal area (Figure 12C) has not changed substantially when compared to the preoperative side.

Discussion

Surgery to the inferior turbinate has been done using a myriad number of techniques [20-23]. These techniques can broadly be grouped into lateral positioning, resection and coagulation. Some of these techniques damage and disturb the mucociliary flow, sensation and climatisation of the air temporarily, if not permanently, to some extent. The inferior turbinates are intended to carry out important functions including heating and humidification of the inspiratory air, as well as provide sensation of airflow both conscious and subconscious. The goal of turbinate surgery should be to improve the patients' complaints of nasal obstruction whilst preserving their physiological function. One major difficulty in turbinate surgery is in balancing the reduction of turbinate tissue with any improvement in nasal airflow. Excessive reduction of the turbinate can lead to desiccation, crusting and paradoxically a reduction in the sensation of airflow through dryness in spite of an improvement in airflow. In severe cases, this can result in the empty nose syndrome.

In vivo studies, as well as simulations of intranasal air conditioning, have shown that the turbinate complex, including the nasal valve area, primarily contribute to nasal air conditioning [24-32] and therefore are thought to be best being preserved wherever possible.

However, septoplasty and septorhinoplasty including a bilateral submucosal anterior turbinoplasty [17] have been shown to provide an improvement in nasal breathing and improved heating and humidification after surgery [17-19]. However, extensive resection or complete resection of the inferior turbinate significantly decreases heating and humidification of the respiratory air [29-32]. Extensive resection of the inferior turbinate can result in a subjective sensation of a blocked nose mainly due to the dryness altering the sensation of airflow, a reduction in the mucosal surface area or a disturbed pattern of airflow along with a large increase in nasal volume. These changes in nasal respiratory flow can misdirect the airflow almost totally through the inferior meatus [31,32]. The inferior turbinate, as part of the nasal valve area, directs the air stream over a wide area of the mucosal surface. Extensive resection of the inferior turbinates significantly disturbs climatization of the inspired air [30,31]. This fact may contribute to crusting, bleeding and nasal dryness, which are frequent complaints of patients after aggressive turbinate surgery. Within the healthy nose, the inspired air passes the nasal valve area changing the laminar airflow into a turbulent one, allowing extensive contact between air and nasal mucosa. The respiratory air is spread all over the mucosal lining of the adjoining turbinate area. Turbulent airflow provides more

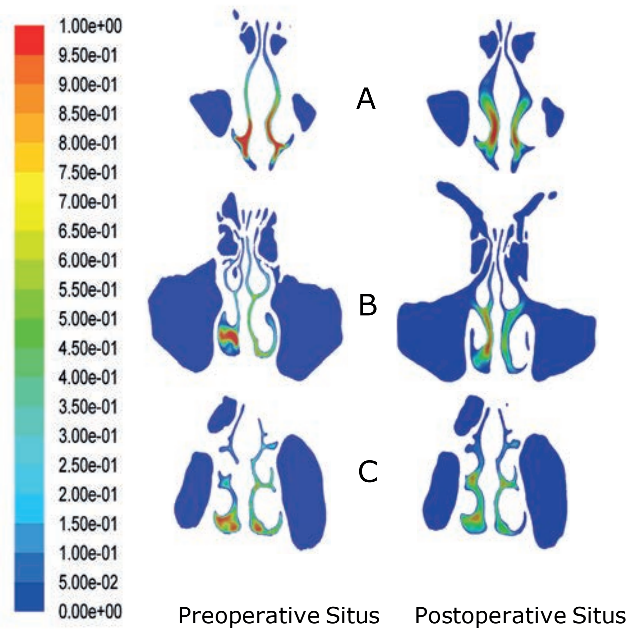

Figure 12. Coronal planes of the nasal model. Profiles of velocity magnitude [m/s] pre- and postoperative next to each other in the
A: Anterior nasal area; B: Middle nasal area; C: Posterior nasal area
Compared to the preoperative situs the airflow is considerably more constant and slower after performing the pyriform turbinoplasty.

kinetic energy than laminar airflow, hence, heat and humidity exchange between inspired air and nasal mucosa is more effective and intense in area of the turbulences. If the anterior head of the inferior turbinate is removed, this can lead to a reduction in air to mucosa contact because it can produce a more laminar airflow. The lack of multiple small vortices with sideway motions that normally ensure intensive contact between air and mucosa can be responsible for impairing heat and water exchange.
Numerical simulation of airflow and air conditioning in realistic nose models after turbinate resection have revealed that these changes in heating and humidification can cause a disturbance in airflow patterns [31,32]. These numerical simulations underline the close relationship between airflow patterns and air conditioning, which depend on the inferior turbinate. There is little consensus about which, if any, turbinate surgery is best. It would appear desirable that the mucosa of the inferior turbinate is damaged as little as possible to help preserve its physiological functions, including sensation.
When talking about turbinate surgery the boundaries of the nasal valve area are usually not taken into account. In addition to the septum medially and the upper lateral cartilage laterally, the lateral margin includes the "pyriform aperture complex". This complex can vary depending on the position and thickness of the frontal process of the maxilla, the lacrimal bone, the rim of the pyriform aperture and the anterior bony aspect of the inferior turbinate.

In this context, we present a new technique "pyriform turbinoplasty" as a technique to improve airflow through the nasal valve area yet maintain physiological function. The "pyriform turbinoplasty" includes a submucosal resection of the frontal process of the maxilla and part of the lacrimal bone as well as partial resection of the "shoulder" of the IT. Typical indications are narrowing of the nasal valve area where the pyriform aperture impinges on the nasal airway or mucosal hypertrophy in the nasal valve area, which is unresponsive to medical treatment. Numerical simulation of the intranasal airflow illustrate that a uniform and improved airflow throughout the entire nose occurs after "pyriform turbinoplasty". The airflow is distributed in an improved physiological manner as well as preserving the turbinate complex. This is in contrast to the above described changes in airflow due to extensive resections of the turbinate. The respiratory air is still distributed all over the mucosal lining because the head of the inferior turbinate preserves contact between air and mucosa.

Conclusions

"Pyriform turbinoplasty" is the submucosal reduction of the bone of the frontal process of the maxilla and the lacrimal bone. This resection of bone can be extended by "nasal wall lateralization" when the lacrimal bone that joins the uncinate process behind the lacrimal duct, as well as the base of the inferior turbinate and the edge of the maxilla at the rim of the pyriform aperture are removed. These procedures open the nasal valve area.
Numerical simulation using computational fluid dynamics and ANSYS Fluent solver show that these procedures produce an increase in airflow and as a result lower airspeeds. These procedures help ventilation in the main flow areas without substantially altering the normal pattern of airflow. These changes appear to be an improvement to the changes in nasal respiratory flow produced after inferior turbinate surgery that can misdirect the airflow almost totally through the inferior meatus and lead to crusting and, paradoxically, a reduction in the sensation of airflow through dryness in spite of an improvement in airflow. Turbinate surgery also tends to achieve only short term changes as the mucosa re-hypertrophies whereas pyriform turbinoplasty widens the lateral bony margin of the nasal valve area.

Author contributions

DS and FS contributed equally to this manuscript (shared authorship). HRB, NJ, TKH assisted in the preparation of this manuscript. JL is the senior author of this manuscript.
All authors have read and approved the submission of the manuscript.

Conflict of interest

The manuscript has not been published and is not being considered for publication elsewhere, in whole or in part or in any language. None of the authors have financial or other kinds of interests that might pose a conflict of interest in connection with the submitted article.

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