JAAKKO ORMISKANGAS

Computational Fluid Dynamics and Experimental Methods of Nasal Airflow in Rhinological Patients

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Computational Fluid Dynamics and Experimental Methods of Nasal Airflow in Rhinological Patients

ACADEMIC DISSERTATION
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Tampere, April 2024

Jaakko Ormiskangas
ABSTRACT

Chronic nasal congestion is a common problem in the general population. Conservative treatment of nasal congestion is usually based on medication. However, those patients not responsive to medication can be surgically treated. In addition to the careful assessment of the clinical status of rhinological patients, rhinometric measurements have traditionally been used as objective methods for evaluating the nasal cavities. The most common rhinometric measurements are acoustic rhinometry and active anterior rhinomanometry. All objective measures aim to help the clinician and increase objectivity. However, the correlation between objective and subjective measures is known to be inadequate.

A more detailed and relatively new way of analysing nasal congestion is based on evaluating accurate three-dimensionally imaged nasal cavities. Nowadays, the most used accurate imaging methods are computed tomography (CT) and cone beam computed tomography (CBCT) scans. In its simplest form, the analysis of these images can be done two dimensionally from anterior to posterior using visual inspection. Despite the practicality of two-dimensional analysis in observing images, nasal cavities and nasal airflow are complex in three-dimensional geometry. Nasal airflow within the nasal cavities can be studied with fluid mechanics methods, which are common in engineering sciences, but until recently these methods have not been used for analysing rhinological patients. The aim of this dissertation is to examine the applicability of computational and experimental methods for measuring nasal cavity airflow and to study the relationship between objective volumetric and nasal airflow variables and the subjective responses of patients pre- and postoperatively.

In all studies, the inclusion criteria for patients were chronic nasal congestion with bilaterally enlarged inferior turbinates. In the first study, imaging data of five preoperative patients were replicated in nasal 3D prints. The success of replication was studied by comparing in vivo and in vitro results in CBCT scan measurements and in active anterior rhinomanometry. In the second study, the preoperative imaging data of one patient were selected for producing a silicone model for the Particle Image Velocimetry (PIV) measurements and for comparing the obtained results with CFD calculations. In the third study, inferior turbinate surgery results were evaluated
preoperatively and at 12 months postoperatively by conducting volumetric and cross-sectional measurements of the operated area. In the fourth and the fifth studies, nasal airflow of inferior turbinate surgery patients were studied with CFD calculations preoperatively and at 12 months postoperatively. The CFD results were compared to the subjective severity of nasal obstruction Visual Analogue Scale (VAS) and Glasgow Health Status Inventory assessments.

The experimental methods (plastic 3D prints and PIV experiments) produced good results for clinical purposes and those methods can be used in modelling nasal airflow. Further improvement is, however, needed in producing the physical models. It was found that CFD calculations can be used to study nasal cavity airflow, as these calculations were able to reveal differences in nasal airflow after surgery. Furthermore, changes in CFD objective results and subjective nasal patency VAS score had a significant correlation with wall shear forces in the operated area after inferior turbinate surgery.

CFD is a promising tool for nasal airflow analysis that could be used in clinical practice after an improvement in CFD workflow. Further, imaging data have a lot of unused potential in the evaluation of patients. CFD requires patient imaging and enables new possibilities for analysing patients and the correlations with the patients’ subjective nasal patency. In addition, future clinical evaluation of patients should aim to collect the patient data needed for CFD calculations as boundary conditions. This would help to ensure the correct boundary conditions for a detailed study of the nasal airflow against the patients’ subjective feeling of nasal patency.
TIIVISTELMÄ


Yksityiskohtaisempi ja uudempi keino nenän tukkoisuuden tutkimisessa ovat tarkat kolmiulotteiset kuvantamistutkimukset. Suositteimmat näistä menetelmistä ovat tietokonetomografia (TT) ja kartiokeilatietokonetomografia (KKTT). Yksinkertaisimmillaan kuvantamisia voidaan katsoa kaksiulotteisesti edestä taaksepäin nenäkäytävien visuaalisen ymmärtämyksen lisäämiseksi, vaikkakin nenäkäytävissä on monimutkainen kolmiulotteinen geometri. Lisäksi nenäkäytävissä tapahtuvaa ilmavirtausta voidaan tutkia virtaustekniikan menetelmissä potilaskuvista. Virtausmekaniikan menetelmät ovat laajasti käytössä insinööritieteiden aloilla, mutta rinologisten potilaiden tutkimisessa näitä menetelmiä ei ole juurikaan hyödynnetty. Tämän työn tarkoituksena on tutkia virtautensa kokeellisen ja laskennallisen menetelmien kykyä nenän ilmavirtauksen arviointissa sekä tutkia objektiivisten ja potilaan subjektiivisten arviointien korrelaatioita ennen ja jälkeen nenäleikkausten.

viidennessä osatyössä samalle potilasjoukolle tehtiin virtauksen numeeriset laskennat (CFD) sekä verrattiin objektiivisten virtauslaskentojen ja subjektiivisten vasteiden korrelaatioita.


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<td>ABS</td>
<td>Acrylonitrile butadiene styrene</td>
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<td>CFD</td>
<td>Computational fluid dynamics</td>
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<td>CBCT</td>
<td>Cone beam computed tomography</td>
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<td>CT</td>
<td>Computed tomography</td>
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<td>DICOM</td>
<td>Digital imaging and communications in medicine</td>
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<td>DNS</td>
<td>Direct numerical simulation</td>
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<td>FDM</td>
<td>Fused deposition modelling</td>
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<td>GBI</td>
<td>Glasgow benefit inventory</td>
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<td>GHCSI</td>
<td>Glasgow health status inventory</td>
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<td>HF</td>
<td>Heat flux</td>
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<td>Heat transfer</td>
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<td>HU</td>
<td>Hounsfield unit</td>
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<td>ITH</td>
<td>Inferior turbinate hypertrophy</td>
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<tr>
<td>LBM</td>
<td>Lattice Boltzmann</td>
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<td>LES</td>
<td>Large eddy simulation</td>
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<td>LDA</td>
<td>Laser doppler anemometry</td>
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<td>LOS</td>
<td>Least obstructed side</td>
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<td>MCA</td>
<td>Minimal cross-sectional area</td>
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<td>MOS</td>
<td>Most obstructed side</td>
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<tr>
<td>MRI</td>
<td>Magnetic resonance imaging</td>
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<td>NAO</td>
<td>Nasal airway obstruction</td>
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<td>NOSE</td>
<td>Nasal obstruction symptom evaluation</td>
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<td>PIV</td>
<td>Particle image velocimetry</td>
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<td>PLA</td>
<td>Polylactic acid</td>
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<td>PVA</td>
<td>Polyvinyl alcohol</td>
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<td>QOL</td>
<td>Quality of life</td>
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<tr>
<td>RANS</td>
<td>Reynolds averaged Navier-Stokes</td>
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<td>RFTA</td>
<td>Radiofrequency thermal ablation</td>
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<tr>
<td>SAHF50</td>
<td>Surface area where heat flux exceeds 50 W/m²</td>
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<td>SD</td>
<td>Septal deviation</td>
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<tr>
<td>SLA</td>
<td>Streolithography</td>
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<td>SNOT-22</td>
<td>22-item sinonasal outcome test</td>
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<td>SPIV</td>
<td>Stereoscopic particle image velocimetry</td>
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<tr>
<td>STL</td>
<td>Standard tessellation language</td>
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<td>VAS</td>
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<td>W-F</td>
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LIST OF ORIGINAL PUBLICATIONS

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Publication III

Publication IV

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* Equal contribution from authors

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AUTHOR’S CONTRIBUTION

Publication I  The author took part in the study design, processed all the data and contributed to the manuscript. The author is the second author in this publication.

Publication II  The author took part in the study design, produced the silicone model and constructed the experimental setup. The author measured and analysed all the experimental data and conducted the CFD calculations. The author wrote the manuscript. The author is the main author in this publication.

Publication III  The author took part in the study design. The author produced, with the equal contribution of a co-researcher, the 3D modelling of all the patient CBCT scans, volumetric measurements based on 3D models and measured the cross-sectional areas from patient CBCT scans. The author is the main author in this publication with the equal contribution of a co-researcher.

Publication IV  The author took part in the study design and conducted CFD calculations with post-processing analysis and statistical analyses. The author wrote the manuscript. The author is the main author in this publication.

Publication V  The author took part in the study design and conducted CFD calculations with post-processing analysis and statistical analyses. The author wrote the manuscript. The author is the main author in this publication.
1 INTRODUCTION

A functioning nasal cavity is essential for the well-being of humans. In addition to the main respiratory functions and smell, the nasal cavity traps particles, eliminates pathogens, and humidifies and tempers the incoming air while inhaling. When exhaling, the nasal cavity gathers moisture and heat. A feeling of nasal congestion is common among individuals. The problems of nasal congestion mainly exist at rest because individuals breathe through the mouth during exercise. The main treatments for chronic nasal congestion are medication or nasal surgery.

Patient imaging is known to benefit the analysis of nasal congestion in affected patients. However, in the assessment and surgical treatment of nasal congestion, clinicians still operate under good practices and intuition. Unfortunately, in many cases, it is not always clear whether patient subjective assessment correlates well with objective measurements (André et al., 2009), although the aim of objective measures is to enhance patient assessment. Rhinometric measurements have traditionally been used as objective methods in evaluating the nasal cavities. The most common of these methods are acoustic rhinometry and active anterior rhinomanometry. Both methods can reveal unilateral information. Acoustic rhinometry obtains two-dimensional (2D) cross-sectional areas along the nasal cavities without detailed information. Active anterior rhinomanometry obtains the unilateral flow resistances of the nasal cavities, also without detailed flow information. The separate information can then be combined to obtain total nasal airflow resistance. In summary, the information obtained from rhinomanometric studies is not detailed enough for the study and planning of nasal surgeries. There is, therefore, a strong demand for objective evaluations and improved surgical help for the clinicians.

A more detailed and a relatively new way of analysing nasal congestion is based on evaluating accurate three-dimensionally (3D) imaged nasal cavities. This 3D information on the anatomy of the nasal cavities is not obtained in rhinomanometric studies. Nowadays, the most used accurate imaging modalities are computed tomography (CT) and cone beam computed tomography (CBCT) scans. The latter has a smaller radiation dose and all the images of patients included
in this dissertation were obtained using this method. At the simplest level, analysis of these static images can be performed two-dimensionally from anterior to posterior by visual inspection. Despite the practicality of the two-dimensional analysis used in observing images, nasal cavities are complex in three-dimensional geometry. In addition, nasal airflow within the nasal cavities can influence the patients’ subjective feelings of nasal patency. Although nasal airflow can be studied with fluid mechanics methods, which is a traditional field of engineering, these methods were not used for analysing rhinological patients until recently.

The information obtained from imaging scans can be used to comprehensively study nasal airflow in the nasal cavities. In general, fluid mechanics can be studied with experimental measurement methods or with computational methods. As nasal cavities are complex and three-dimensional, 3D printing has enhanced in vitro experimental studies of nasal airflow in recent years because complex geometries can be replicated for the measurements. Furthermore, the patient images obtained could be used to study nasal airflow by conducting Computational Fluid Dynamics (CFD) calculations. Nowadays, experimental fluid mechanics studies are mainly used to validate CFD turbulence models or other CFD modelling assumptions. Typically, these calculations are done in inspiratory airflow, as patients feel inspiratory breathing is the most troublesome. However, although all breathing conditions can be studied, the computational and experimental costs are higher. Currently, CFD calculations are time consuming and require technical expertise. Therefore, the first aim of this dissertation is to examine the applicability of computational and experimental nasal cavity airflow methods. A second aim is to study the relations between objective volumetric and nasal airflow variables and the patients’ subjective responses preoperatively and postoperatively. Postoperative imaging information acquired from patients is scarce, as these images are not usually gathered in daily practice.

To date, only a small amount of 3D data is used in clinical practice. Thus, clinicians are left to cope with only their experience, intuition and subjective assessment of how to operate during surgery. It is, of course, practically impossible for the surgeon to evaluate the fluid mechanical consequences of each surgical manoeuvre due to the complexity of the nasal cavities. Moreover, no automated data process exists that could obtain and convert proper information from rhinomanometric measurements or static patient images to nasal airflow CFD studies. Different inferior turbinate surgery methods have, however, been investigated and found to be equally good while winning placebo effect (Harju et
al., 2018). Even better surgery results could be expected with proper guiding software for surgeries.
2 REVIEW OF THE LITERATURE

2.1 Anatomy and physiology of the nose

2.1.1 Anatomy of the nasal cavities

The anatomy of the nose consists of the nasal cavities and the paranasal sinuses (Figure 1), whereas the anatomy of the anterior nasal cavities consists of two distinct nasal cavities separated by the nasal septum. The nasal septum ends posteriorly in the choanae, where two nasal cavities merge and the nasal cavity opens posteriorly to the nasopharynx.

Figure 1. Upper respiratory tract (Blausen.com staff (2014). "Medical gallery of Blausen Medical 2014". *WikiJournal of Medicine* 1 (2). DOI:10.15347/wjm/2014.010. ISSN 2002-4436.) This work is openly licensed via CC BY 3.0.
The nasal cavities are surrounded on both the left and right sides by the paranasal sinuses, which include the ethmoidal sinuses, the frontal sinuses and maxillary sinuses, and the sphenoidal sinuses (Figure 2).

![Paranasal sinuses](image)

**Figure 2.** Paranasal sinuses. Adapted from the original source (Komorniczak M). Original work is openly licensed via CC BY SA 3.0.

The surface of the mucous membrane increases from complex turbinate structures (also known as conchae). Inferior turbinates have been found to be climate dependent and, as a result, increase heat transfer (Marks et al., 2019). The turbinates are divided vertically to inferior, middle and superior turbinates. Above the turbinates lie the ethmoidal sinuses. The most minimal coronal cross-sectional areas lie at the level of the nasal valve and in the head of the inferior turbinate. The nasal valve is located posterior from external nares, but anteriorly from the nasal turbinates.
Averaged anatomies of the nasal cavities have been studied within and between groups. An averaged nasal cavity of a Caucasian nose was created by Liu et al. (2009). Similarly, Lee et al. (2013) standardised a Malaysian female nasal cavity. A more detailed study of the anatomy of the nasal cavities can be made with statistical shape models, which include all the shape modes of noses and their variations. Keustermans et al. (2018) and Brüning et al. (2020) have created standard cavities from a homogenous healthy cohort of volunteers by using statistical shape modelling. Evtseev et al. (2019) studied the morphology of the nasal cavities of different Asian populations, whereas Marechal et al. (2022) studied the variability of the upper airway in modern humans in different climate conditions in Chile, France, Cambodia, South Africa, Russia and South Africa. Furthermore, males have larger airway volumes than females and age had an effect on nasal morphology. In another study without statistical shape modelling, age did not, however, affect the volumes of the nasal cavities (Wang et al., 2023).

2.1.2 Physiology of the nose

The function of the nose is to humidify and heat the inspiratory air and to remove pathogens. The nose is a part of facial appearance and an essential part of breathing routes. For humans at rest, the nose is a primary breathing route. For breathing in more extreme conditions, the oral route becomes more dominant. While the nose warms, humidifies and filters the inspiratory air, during exhalation, the nose condenses the expiratory air, thereby saving water resources (Mygind & Dahl, 1998). Furthermore, the nose is also responsible for olfactory function. The olfactory function is located at the superior parts of the nasal cavities and is a central part of the well-being of humans.

In calm conditions and especially with healthy humans, breathing happens fully via the nose. However, during exercise humans breathe partly via their mouth. At rest, humans breathe 12-18 cycles per minute, where inspiratory and expiratory phases follow each other with a rough tidal volume of 0.5 litres. A more detailed flow rate has also been obtained as a function of gender and weight (Garcia et al., 2009).
2.1.3 Sense of nasal patency

The sense of nasal patency is subjective and greatly dependent on the subject and the period of the assessment. The individual variation in the subjective feeling of nasal patency is large. To the best of our knowledge, only one study has been conducted where subjective assessment of the nasal cavities was tested at two consecutive times under the same conditions (Zhao et al., 2014). In that study, the correlation coefficient between two consecutive bilateral nasal patency measurements was found to be 0.75.

For the nose to feel pleasant, the nose must be wide enough but not too wide, as nasal cavities that are too wide could paradoxically also feel congested. The assessment of nasal patency can be made unilaterally or bilaterally. Interestingly, some studies have assessed unilateral nasal patency by closing the other side of the nostrils at the time of the assessment (Casey et al., 2017; Sullivan et al., 2014; Gaberino et al., 2017).

Different substances can also influence subjective nasal patency. Receptors of the trigeminus nerve have the effect of transferring objective flow variables at the surface of the mucous membrane to psychophysical sensing. To date, very few studies exist where receptor effects are studied among humans. Menthol has been found to have no effect on nasal resistance and airway volumes (Eccles et al., 1983). Menthol was, however, found to improve subjective nasal patency. Similarly, Lindemann et al. (2008) studied the effects of menthol on nasal functions in healthy volunteers. They found that menthol affected the sense of subjective nasal patency but did not affect the nasal resistances in active anterior rhinomanometry or nasal mucosal temperatures.

In addition to substances, posture might also change the sense of nasal patency. Roithmann et al. (2005) found that changing position from a sitting position to a supine position alters nasal perception for the worse in both healthy subjects and patients with rhinitis.

2.1.4 Nasal cycle and its modelling

The nasal cycle is a spontaneous unilateral or bilateral congestion and decongestation of the mucous membrane that evolves with time and affects nasal airway volumes. Several types of nasal cycle exist, including classic, parallel, irregular and no nasal cycle at all (Anselmo-Lima & Lund, 2001). A classic nasal cycle is a reciprocal congestion and decongestion of the nasal cavities where total
nasal volume does not change. Parallel nasal cycle, in contrast, is a simultaneous congestion and decongestion of both nasal cavities. Between 70% and 80% of humans have been found to have a nasal cycle (Hasegawa & Kern, 1977; Heetderks, 1927). A nasal cycle is expected to last from 30 minutes to 6 hours (Gungor et al., 1999) Regardless of the type of nasal cycle, patients are not usually aware of the nasal cycle (Pendolino et al., 2018).

2.1.5 The effect of environmental conditions on subjective assessment and temperatures of the nasal mucosa

In clinical practice, patients are typically studied in a sitting or standing position at rest. For typical indoor conditions, Lindemann et al. (2002) studied 15 healthy volunteers and the temperatures from intranasal sites with expiratory and inspiratory airflow. The environment was at a room temperature of 25 °C and relative humidity of 30%. The measurement sites were at the nasal vestibule, the nasal valve area, the anterior turbinate area and the nasopharynx. The highest temperatures at the intranasal sites were found at the end of expiratory breathing and the lowest temperatures were found at the end of inspiratory breathing. Statistically significant differences were found between the different intranasal sites. The lowest temperatures between the intranasal sites were at the nasal valve area and at the anterior turbinates, while the highest temperatures were at the nasopharynx. The temperatures at the end of inspiratory breathing were 30.2 ± 1.7 °C and 33.2 ± 2.3 °C. At the end of expiratory breathing the temperatures were 32.5 ± 1.1 °C and 34.4 ± 1.1 °C.

Breathing volume flowrates could affect mucosal temperatures. Lindemann et al. (2007) studied the relation between rhinomanometric resistances and mucosal temperatures in healthy subjects. They found a negative correlation between nasal airflow rate and mucosal temperatures at the ends of the inspiratory and expiratory respiratory cycles. No statistically significant differences, however, were found between the left and right sides of the nostrils. A thermosensor was located within the area of the anterior turbinate.

It might be argued that different climate conditions effect the overall quality of life of rhinological patients. To date, only a few studies exist in which a detailed study has been conducted on the overall quality of life as a function of seasons. NOSE-22 scores have been found to be independent from climate conditions in Southern Finland (Ylivuori et al., 2021). It was concluded that there was no
significant seasonal variation in rhinological symptoms or diseases when analysed in a country with four distinct weather seasons.

The typical daily life might, however, be somewhat different from conditions in clinical practice. Liener et al. (2003) studied the effects of different environmental conditions on intranasal mucosal temperatures. They found that significant changes occurred as the result of different climatic exposure. Cold air leads to decreased mucosal temperatures and warm air leads to increased mucosal temperatures. The measured sites were at the nasal vestibule, the nasal valve area, the anterior turbinate area and the choanae. The mucosal temperature gradient decreased from the anterior to the posterior region. The median temperature in the anterior turbinate area at the end of inspiratory breathing was 30.2 °C for normal temperatures and 28.2 °C for cold dry air. Zhao et al. (2011) found that dry air does not change bilateral subjective nasal patency but cold air increases nasal patency. Yogeetha et al. (2007) found that normal room temperatures decrease subjective nasal patency and increase nasal resistances as measured by acoustic rhinometry compared to warm temperatures of 30-33 °C in healthy subjects.

2.1.6 Nasal valve collapse and the elasticity of the mucous membrane

The mucous membrane of the nasal cavity is elastic and dependent on breathing conditions and other environmental factors. During the breathing cycle, inspiratory breathing lowers the pressure in the nasal cavities, which can create collapsible effects on the mucous membrane. Conversely, in expiratory breathing, pressure increases and the mucous membrane might be decongested. The general elasticity of the mucous membrane is, however, rarely directly studied. This observation could, in principle, be revealed from anterior rhinomanometric results. Nasal valve collapses are, however, practically always diagnosed in clinical practice. Gagnieur et al. (2022) studied patients with and without internal nasal valve collapse from the hysteresis loop areas in 4-phase rhinomanometry. Both nasal cavities were analysed together for each patient with and without decongestant. The inspiratory loop area of 4-phase rhinomanometric curves was significantly higher in patients with nasal valve collapse than those who had a different cause of rhinological symptoms. The results suggest that nasal valve collapse can be identified with high sensitivity and specificity from rhinomanometric data.

Dynamic imaging is rarely employed in the field of otorhinolaryngology and these images are not gathered in clinical practice. For research purposes, Bates et
al. (2019) studied dynamic airway motion from the fast cine Magnetic Resonance Imaging (MRI) scans of a healthy volunteer. The volunteer was asked to breathe at non-maximal effort through his nose or mouth, or any combination of the two. It was found that the airway demonstrated both neuromuscular activity and aerodynamic forces. The study also showed the importance of incorporating both types of motion into CFD calculations.

2.2 Rhinological patient and examination of symptoms

2.2.1 Examination of a rhinological patient

Examination of a rhinological patient typically includes anterior rhinoscopy and mirror aided posterior rhinoscopy. In addition, inspection of nasal valve collapse can also be made visually. The inspection of nasal valve collapse is, therefore, challenging. For the imaging of patients, comprehensive technical imaging examination is based on X-ray, such as CT or CBCT imaging, or in more rare cases MRI images.

2.2.2 Nasal obstruction

Nasal obstruction is described as a patients’ experience of facial fullness or insufficient airflow through the nose. The extent of the nasal obstruction can change between the sitting and supine positions or as the result of muscle tonus (Roithmann et al., 2005). Mucosal inflammation is often responsible for these symptoms. Alternatively, symptoms can stem from abnormalities in the nasal cavity or abnormal sensory perceptions. The most typical causes of nasal obstruction are acute or chronic rhinosinusitis, rhinitis, polyposis and septal deviations and concha bullosa. Rhinitis can be further divided into several other types, including iatrogenic, atrophic, tumoral, infectious, inflammatory, vasomotor and hormonal (Gelardi et al., 2023). The sensation of nasal patency does not correlate well with objective measures (André et al., 2009).
2.2.3 Subjective measures of nasal obstruction

Various subjective measures exist for subjectively assessing the nasal cavities. These measures are usually continuous and bounded, or in Likert scale. They are usually based on well-known scores such as the Visual Analogue Scale (VAS) and the Sino-Nasal Outcome Test (SNOT-22) or the Nasal Obstruction Symptom Evaluation (NOSE) and the Glasgow Heath Status Inventory (GHSI). In these studies, patients fill out a questionnaire to subjectively assess the nasal cavities. All measures are subjective and dependent on several life and environmental conditions.

2.2.3.1 Visual Analogue Scale (VAS)

The VAS scale is often used to assess subjective nasal patency and other factors. The most used subjective measure in rhinological patients is the severity of nasal obstruction VAS. The VAS scale is usually continuous and bounded. Typically, the scale is defined from 0 to 10, where 0 means the nasal passages are completely open and 10 completely blocked. Assessments can be made instantaneously or for a longer period. The nasal cavities can be evaluated unilaterally or bilaterally. Interestingly, some studies have used the blockage of the other nostril while assessing the unilateral severity of the nasal obstruction VAS (Casey et al., 2017; Sullivan et al., 2014; Gaberino et al., 2017). VAS assessment is always very subjective and suffers from confounding factors such as placebo effect (Harju et al., 2018).

2.2.3.2 SNOT-22 and NOSE

The most used survey for general quality of life for patients with rhinological disease, and especially for patients with chronic rhinosinusitis, is SNOT-22. The SNOT-22 has been validated in Finnish (Koskinen et al., 2021) and is often used for the assessment of chronic rhinosinusitis. The SNOT-22 includes 22 questions on a scale from 0 to 5. Healthy subjects obtain an average of 9 points from this questionnaire (Koskinen et al., 2021).

In contrast, the NOSE questionnaire is better suited for assessing the severity of nasal congestion. NOSE surveys in nasal airflow studies typically have questions such as: Over the past month have you experienced 1) nasal congestion or
stiffness 2) nasal blockage or obstruction 3) trouble breathing through nose 4) trouble sleeping and ability to get enough air through the nose during exercise or exertion. A Likert scale of 0 to 4 is usually used. These results are then summed and multiplied by 20. This results in 0 being the best case and 100 the worst. In nasal congestion studies, SNOT-22 is evaluated over the previous two weeks, whereas NOSE surveys are usually gathered from the previous month.

2.2.3.3 GHSI and GBI

GHSI is a general quality of life assessment. GHSI is evaluated before and after a surgical procedure. Very similar to GHSI, the Glasgow Benefit Inventory (GBI) is only evaluated after the surgical procedure. The basic questions on both questionnaires are the same and can be modified for several different surgical procedures. The GHSI score is from 0 to 100, and the GBI score is from -100 to 100.

2.2.4 Objective rhinometric measurements

Rhinometric measurements is a general term for certain objective measurements performed in the nasal cavities. The most usual rhinometric measurements are acoustic rhinometry and active anterior rhinomanometry, which obtain results separately from both sides of the nasal cavities. Objective rhinomanometric measurements are usually gathered preoperatively with and without vasoconstriction and can reveal mucous inflammation and anatomic abnormalities. Typically, vasoconstriction with xylometazoline is used to evaluate the effects of the planned treatment preoperatively. The usual threshold for selection for inferior turbinate surgery is a 30% increase in airway volumes after applying decongestant (Harju et al., 2018).

2.2.4.1 Acoustic rhinometry

Acoustic rhinometry, first introduced by Hilberg et al. (1989), is an objective and non-invasive method for assessing the cross-sectional areas of the nasal cavity as a function of distance from the nostrils. Acoustic rhinometry is based on sound
waves and acoustic reflection. It has been reported that the accuracy of acoustic rhinometry measurement deteriorates posteriorly (Numminen et al., 2003).

While acoustic rhinometry obtains cross-sectional area results as a function of distance from the nostrils, the results are often presented as volumes between certain distances within the nasal cavity, such as V2-5 cm, or in minimal cross-sectional areas along the nasal cavities. Two minimal cross-sectional areas, MCA1 and MCA2, are often mentioned separately or as a sum for both nasal cavities. MCA1 is the first minimal cross-sectional area posteriorly from the nostrils that is usually located at the level of nasal valve. MCA2 is the second minimal cross-sectional area that is usually located at the head of the inferior turbinate.

Acoustic rhinometry is usually conducted in a seated position. It should be noted, however, that rhinometric results can change between the sitting position and the supine position, as was observed in acoustic rhinometry results (Roithmann et al., 2005). Roithmann et al. (2005) found that a change from a sitting position to a supine position decreased nasal airway volumes.

2.2.4.2 Active anterior rhinomanometry

Active anterior rhinomanometry is the current gold standard in measuring airflow resistances and objective nasal patency. Active anterior rhinomanometry obtains unilateral global nasal airflow resistances from the nostrils to the choanae. Therefore, no detailed local information of the pressure field is obtained. Airflow resistance is defined as a ratio between pressure loss and volume flow rate. The measurement is conducted unilaterally by separately assessing the nasal cavities. When taking the measurements, one of the nasal cavities is blocked while the flow resistance of the open nasal cavity is measured. During the measurements, the patient’s mouth is closed, and all breathing routes are typically surrounded by a mask. The pressure difference between the mask and the closed nostril is then measured. The measurement is continuous and usually lasts for several breathing cycles, after which the results are averaged. Total bilateral resistance can be calculated from unilateral resistances by using the analogy of parallel resistors.

While active anterior rhinomanometry obtains resistances continuously for each pressure drop or volume flow rate produced, several different styles exist for analysing the results. The typical method of analysing the results is at a predefined level of pressure drop 75 Pa or 150 Pa. Various other methods, such as Broms’ method calculated at a round circle of radius 200 in a graph composed of volume flow rate [cm³/s] and pressure loss [Pa], also exist (Figure 3). In addition, peak
resistance results from the largest pressure drop can also be reported. The 4-phase resistance (4PR) results are calculated from the whole breathing cycle. Vogt et al. (2016) studied the distribution of rhinomanometric resistances and found that in a logarithmic scale, normal distribution of the results was obtained with a large population.

**Figure 3.** Active anterior rhinomanometry curves with Broms’s method (round circle at a radius of 200 cm$^3$/s and 200 Pa). Pressure is presented in the x-axis and airflow volume flow rate in the y-axis. The graph includes separate curves for left and right nostrils. Inspiration results are presented on the right side and expiration results on the left side.

The reproducibility of the rhinomanometric measurements in quick succession is rarely studied. Carney et al. (2001) studied reproducibility with consecutive
measurements and found that a high coefficient of variation (19% to 60%) was observed in a basic protocol while a revised Nottingham protocol obtained a reduced coefficient of variation (7% to 15%) when, for instance, air leakage was better considered.

2.2.4.3 Active posterior rhinomanometry

Active posterior rhinomanometry is conducted by inserting a pressure tube inside the mouth or to the nasopharynx via the mouth while the patient typically breathes simultaneously on both sides of the nasal cavities. Posterior rhinomanometry generally evaluates both sides of the nasal cavities simultaneously with the mouth closed. This method, however, is prone to faults and taking the measurements requires lots of professional skill. An insufficiently tight grip of the mouthpiece of the differential pressure transducer can lead to air leakage between the mouthpiece and the patient’s lips. Another source of error is the closing of the mouthpiece pressure outlet with the tongue or the strong compression of it (Avrunin et al., 2021). Therefore, the method is rarely used. In principle, posterior rhinomanometry can also be used to separately study the nasal cavities as in active anterior rhinomanometry (Flanagan & Eccles, 1997).

2.2.5 Imaging of the nose and paranasal sinuses

Imaging in otorhinolaryngology is usually recorded in stationary images, where the patient breathes calmly. The most traditional method of obtaining images is sinus X-ray that results in one image of the nasal cavities. This is, why the quality of the sinus X-Ray remains quite low. Recently, however, newer three-dimensional methods, such as CT, CBCT and MRI imaging, have mainly replaced traditional sinus X-Ray images. In the imaging of the nose and paranasal sinuses, CBCT images are acquired while the patient remains in a standing position. In contrast, CT or MRI images are usually acquired with the patient in a supine position. Usually, imaging in patients with nasal congestion is done at the floor level of the nasopharynx. The roof of the image is typically located at the level of the upper margin of the frontal sinuses. In clinical use, these images are usually assessed in 2D scans from different (axial, coronal, sagittal) planes. 3D imaging information is usually saved in the Digital Imaging and Communications in Medicine (DICOM)
format. A coronal cross-section image of the nasal cavities in the DICOM format is presented in Figure 4.

2.2.5.1 Computed tomography (CT) and Cone beam computed tomography (CBCT)

CBCT was first introduced for use in dental imaging. CT imaging lasts longer than CBCT, and the subsequent radiation dose is higher. Compared to MRI scans, inner soft tissue information is limited in CBCT and CT images. Nowadays, ultra-low-dose CBCT devices are also used.

![Figure 4.](image.png)

Figure 4. Cone beam computed tomography image of the nasal cavities and paranasal sinuses in the coronal cross-section.

2.2.5.2 Magnetic Resonance Imaging (MRI)

MRI is based on nuclear magnetic resonance (Fatterpekar et al., 2008). The technique can differentiate the condition of mucous membrane tissues. Furthermore, nasal polyps can be distinguished from normal mucous membrane in MRI images. In rhinological patients, MRI is mainly used to identify tumours.
2.3 Medical and surgical treatment of a blocked nose

2.3.1 Medication

The conservative treatment of nasal congestion is based on long- or short-term medication. The most used topical decongestants are xylometazoline and oxymetazoline, which cause blood vessel constriction. This increases nasal airway volumes and reduces nasal mucosa volumes. Clarke et al. (1995) studied the effects of vasoconstriction on VAS assessment and found that vasoconstriction improves the sense of nasal patency. Recently, Cherobin et al. (2021) made a similar finding. These nasal sprays are commonly used for nasal congestion caused by the common cold, rhinosinusitis or rhinitis. Short-term use is recommended for these sprays, as long-term use can lead to rebound congestion. For longer term medication, intranasal corticosteroids administered as nasal sprays are used.

Aside from typical medication, menthol has been found to have an effect on subjective nasal patency. Although no effect on nasal resistances or temperatures has been found, menthol is still used in some cases. (Lindemann et al., 2008) For example, menthol is currently used in medicine and for the treatment of influenza and acute respiratory infection.

2.3.2 Surgical treatment

The surgical treatment of nasal congestion is based on the removal of submucosa in the turbinates, using various methods or septoplasty operations to correct a deviated nasal septum. Depending on the symptoms and level of congestion, turbinate surgeries can be either performed on both sides of the nasal cavities or unilaterally. The aim of turbinate surgery is to create nasal airways that are wide enough but not too wide. Indeed, nasal airways that are too wide can lead to empty nose syndrome, where the nose feels paradoxically congested while being too open. The removal of polyposis can also be performed in the upper parts of the nasal cavities. Cases of chronic rhinosinusitis can be treated with the surgical opening of the paranasal sinuses.

A typical surgery for nasal congestion with no other pathologies is turbinate surgery. The procedure can be performed in different parts of the inferior and middle inferior turbinates, although it is usually performed anteriorly to the inferior
turbinates. The extent of the inferior or middle turbinate reduction varies. It has been found that middle turbinate resection and inferior turbinoplasty in patients with rhinitis result in the same subjective improvements (Wong et al., 2019). The most technically typical way of performing turbinate surgery is radiofrequency thermal ablation (RFTA). All inferior turbinate reduction techniques have been found to produce the same objective and subjective results (Harju et al., 2018). More invasive ways include total turbinectomy, where the whole turbinates are removed.

2.4 Nasal airflow studies

Nasal airflow, as in all fluid motion, is governed by Navier-Stokes equations, which describe viscous fluid motion in time and space. Nasal airflow is a time-dependent phenomena, where inspiratory and expiratory phases follow each other. This airflow can be studied experimentally in 3D models or numerically with Computational Fluid Dynamics (CFD) calculations. The experiments should be used to validate modelling assumptions and various CFD turbulence models. CFD calculations have mostly replaced direct measurements when only the calculation results are needed, and the assumptions are known beforehand.

Nasal airflow governing Navier-Stokes equations can be used with different assumptions. Hence, experimental model validations are needed or alternatively computational studies themselves should be compared with each other to ascertain in which form the equations are applied. Primary modelling assumptions in nasal airflow studies in addition to turbulence models are about flow unsteadiness and compressibility conditions. Sometimes temperatures and moisture boundary conditions are also important when energy and species transport are calculated.

For reasons of convenience, nasal airflow is often studied in steady state conditions, where volume flowrate is estimated to be an average over the inspiratory or expiratory phase of breathing. The question arises whether it is sufficient to study nasal airflow at steady conditions equal to time transient conditions at the same flowrate. Time transient conditions include accelerating and decelerating phases of breathing. Most studies have assumed that this assumption of a quasi-steady flow field is good enough for practical purposes and corresponds well enough to the natural breathing time transient situation with the same volume flowrate. This approximation is made on practical grounds to reduce computational costs in the CFD calculations or to ease the experimental workload.
Typically, nasal airflow is assumed to be incompressible since velocities are small, such as below 5 m/s in all parts of the nasal cavities (Senanayake et al., 2021; Hebbink et al., 2023). CFD studies of nasal airflow are presented in more detail in chapter 2.5.

2.4.1 Experimental methods

Experimental methods for investigating nasal airflow can be used for turbulence model validations or other validations of modelling assumptions. The methods can also be used for direct measurements of nasal airflow instead of computations. Typically, nasal airflow has small Reynolds numbers. It is, therefore, unclear to what extent nasal airflow is laminar or turbulent.

Experimental methods are primarily based on velocity or pressure measurements. Particle image velocimetry (PIV) measurements are typically used for measuring velocities. More rarely used velocity measurement methods include hot-wire anemometry and Laser Doppler Anemometry (LDA). 3D nasal airway models are needed for all methods in experimental work (Table 1).

2.4.1.1 3D Modelling and printing

The use of 3D printed models in the field of rhinology is relatively new. 3D printing is an additive manufacturing process, which is a three-dimensional, additive and layer-by-layer based manufacturing method. Some of the main methods of 3D printing include fused deposition modelling (FDM) and stereolithography (SLA) resin prints. SLA uses ultraviolet (UV) light to produce the model and has better quality than fused deposition modelling. Conversely, fused deposition modelling is an inexpensive way of producing nasal prints. In this method, a heated nozzle extrudes a semi-liquid filament onto a platform layer by layer. Several filaments exist, with each having different material properties. Some of the most used filaments are polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) and water-soluble polyvinyl alcohol (PVA).
**Table 1.** Experimental flow studies in nasal cavity replicas. The term "Hopkins" refers to the method of producing a silicone model by Hopkins et al. (2000). Abbreviations: Stereolithography (SLA), Lattice Boltzmann method (LBM) and Stereoscopic PIV (SPIV).

<table>
<thead>
<tr>
<th>Production method (Scaling)</th>
<th>Measurement &amp; calculation method</th>
<th>Flow rate in vivo (Inspiratory unless otherwise stated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berger et al. (2021c)</td>
<td>LDA and CFD</td>
<td>48 litres/min at each nostril</td>
</tr>
<tr>
<td>Cai et al. (2022)</td>
<td>Pressure and CFD</td>
<td>3/6/12 litres/min</td>
</tr>
<tr>
<td>Chen et al. (2023)</td>
<td>PIV, Pressure and CFD</td>
<td>4/6/8/10/12/14/16 l/min</td>
</tr>
<tr>
<td>Cherobin et al. (2021)</td>
<td>Rhinomanometry and CFD</td>
<td>A function of pressure loss of (75/150) Pa</td>
</tr>
<tr>
<td>Cozzi et al. (2017)</td>
<td>Unsteady SPIV and LES</td>
<td>Unsteady breathing profile</td>
</tr>
<tr>
<td>Hahn et al. (1993)</td>
<td>Hot-film anemometer probe</td>
<td>10.8/33.6/66 litres/min</td>
</tr>
<tr>
<td>Hebbink et al. (2023)</td>
<td>LBM/LES &amp; Pressure</td>
<td>Unsteady breathing profile</td>
</tr>
<tr>
<td>Mylavarapu et al. (2009)</td>
<td>Pressure &amp; CFD</td>
<td>Expiratory 100 l/min</td>
</tr>
<tr>
<td>Spence et al. (2012)</td>
<td>SPIV</td>
<td>Unsteady breathing profile</td>
</tr>
</tbody>
</table>
2.4.1.2 Pressure measurements in nasal 3D prints

As is the case with patients, the pressure measurements in nasal 3D prints can be made in rhinomanometry with a continuous time transient global assessment of flow. Alternatively, pressure measurements can be made along the nasal cavity by inserting pressure tabs on the nasal cavity walls, which obtain more detailed information along the nasal cavities. Similarly to rhinomanometry, these measurements typically obtain relative pressure differences between the ambient outside of the nose and the pressure inside the nasal cavities.

For the rhinomanometry measurements, Cherobin et al. (2021) created 6 replicas of the nasal cavities in 3D prints. The CT scans were obtained after mucosal decongestion. For a pressure drop of 75 Pa, a good agreement in unilateral nasal resistance was found between rhinomanometric and k-ω turbulence model CFD results with a ratio of 0.93 ± 0.07, while having better performance than the laminar model with a ratio of 0.90 ± 0.08.

Hebbink et al. (2021, 2022) created anatomically accurate 3D-printed upper airway geometries. Thereafter Hebbink et al. (2023), who studied transient human upper airway dynamics with a full natural breathing cycle, used a model from previous studies. In total, 23 pressure tabs were inserted along the nasal cavity and compared against Lattice Boltzmann (LBM) and Large Eddy Simulation (LES) calculations. On average, good agreement was observed.

For steady state experiments, Mylavarapu et al. (2009) made static pressure wall measurements from expiratory airflow corresponding to in vivo conditions of 100 l/min. They found that the k-ω turbulence model achieved the best experimental agreement with an average error of about 20 % over all pressure ports along the nasal cavity. Similarly, Cai et al. (2022) studied different turbulent models and found that best agreement against the experiments across the nasal cavity was found with the k-ω and Spalart-Allmaras models. Chen et al. (2023) measured paediatric upper airway pressures after the nasopharynx. They found that the best Reynolds Averaged Navier Stokes (RANS) results were observed with Low Reynolds number k-ω SST models, whereas LES outperformed all RANS models. Underpredictions were, however, observed with all models when compared to the measurements.
Particle Image Velocimetry (PIV) is based on tracer particles that follow a flow field in in vitro experiments. Typically, neutrally buoyant tracer particles have the same density as the flowing liquid within the model and no-slip can be assumed. With the help of a laser light sheet, high-speed cameras are used to obtain two intermittent consecutive images. Tracer particle displacements can be observed between double-images, and cross-correlation algorithms can be applied for the calculation of the velocity fields. Conventional PIV measurements obtains 2-dimensional velocity fields while Stereoscopic PIV (SPIV) can be used with two cameras to obtain 3-dimensional velocity fields.

The process of producing nasal cavity models for subsequent PIV experiments was first introduced by Hopkins et al. (2000). The water-soluble filament PVA was used in FDM printing to produce a negative of the nasal airways inside the silicone. In the PIV experiments, a water-glycerine mixture was used as a liquid, as the index of refraction is the same as in the silicone model. The same procedure was later applied by several authors (Cozzi et al., 2017; Na et al., 2012; Hörschler et al., 2006; Spence et al., 2012). Cozzi et al. (2017) expanded previous works and conducted preliminary measurements with stereoscopic PIV in a silicone model, which included the paranasal sinuses. Zubair et al. (2015) used a slightly different procedure to produce the PIV model and conducted the studies with water as a fluid.

The liquids used in the PIV experiments cannot take into account the compressibility effects present in in vivo conditions. However, the effect of compressibility has been reported to be small in steady conditions (Cal et al., 2017). Further uncertainties in PIV measurements can be divided into a-priori and a-posteriori uncertainties. These random uncertainties in PIV measurements have been studied by several investigators. However, systematic uncertainties have been studied much less. (Sciacchitano et al., 2019)

In addition to PIV measurements, Hahn et al. (1993) studied velocities within the nasal cavities with a hot-film anemometer probe at a model scale of 20. A similar method was used by Berger et al. (2021c) who studied laser doppler velocimetry measurements against Lattice Boltzmann calculations and found good agreement was achieved.
2.4.2 Computational Fluid Dynamics calculations

2.4.2.1 Imaging data and pre-processing

CFD calculations require the pre-processing of patient imaging data. Typically, patient imaged raw data are stored in Digital Imaging and Communications in Medicine (DICOM) format, which describes volumetric information in three dimensions. In these images, Hounsfield (HU) value describes the grey area which corresponds to the different anatomical properties of the mucous membrane, bone or air. Before using the imaging information in nasal airflow CFD studies, the airways must be segmented from other areas. Usually, this is achieved by defining the correct radio density threshold HU value between the airways and the mucous membrane, which is somewhat subjective and dependent on the imaging parameters and the device. Methods for doing segmentations differ from binary threshold-based methods to manual and semi-automatic and automatic segmentations. Optimal threshold might also have interindividual variation (Nakano et al., 2013; Zwicker et al., 2018).

The sensitivity of the nasal airflow results and airway cross-sectional areas as a function of radiodensity threshold was studied by Cherobin et al. (2018). The study was conducted with the same flow rate in all radiodensity thresholds. Furthermore, Quadrio et al. (2015) also studied the radiodensity threshold and its effects on CFD results. The study was conducted with constant pressure drop in all radiodensity thresholds and the flowrates varied. Both Cherobin et al. (2018) and Quadrio et al. (2015) found that nasal airflow results were strongly dependent on HU threshold segmentation values. In addition to the choice of threshold HU value, different software programs and semi-automatic segmentation algorithms can produce slightly different results. These results have also been compared in the literature (Argüello et al., 2019; Alnaser et al., 2016; Lo Giudice et al., 2022).

2.4.2.2 Computational meshes for nasal airflow studies

After successful segmentation of the nasal airways, surface files are formed that describe the geometry of the nasal cavities. In addition, surface smoothing might be needed to ensure the surfaces of the nasal cavities are smooth, and any additional voxels might need to be removed manually. The surface files are most often in Standard Tessellation Language (STL) file format. As a next step, a
computational mesh must be created for the CFD calculations inside the surfaces. The computational mesh consists of computational cells in which Navier-Stokes equations are solved. Meshes exist in several topology styles such as hexahedral, tetrahedral and polyhedral or combinations of these. At the vicinities of the walls, boundary layers are created for the higher gradient areas of the calculations. Furthermore, the computational mesh defines flow inlet, walls and outlet boundaries for the boundary conditions.

2.4.2.3 Mesh and discretisation independence studies

CFD calculations need to be validated in different mesh sizes to obtain grid independence of the results. Usually, this grid independence is studied by simply increasing the number of cells. The type of cells in the mesh is not usually changed when mesh independence is studied. However, Baker et al. (2020) created a systematic method for analysing mesh independence in indoor airflow.

While mesh independence is often investigated, the effect of the different discretisation schemes on nasal airflow CFD results is studied far less. Schillaci et al. (2022) studied different discretisation schemes on the nasal airflow geometry of a single healthy adult in both inspiratory and expiratory airflow. For reference results, second-order LES was chosen. First-order discretisation resulted in large pressure drops of up to 50% along the nasal cavity compared to second order discretisation. Furthermore, the LES calculations resulted in smaller pressure drops than the laminar and k-ω SST RANS models. It was noted that while the choice of correct turbulence model is important, the correct discretisation scheme is even more important for nasal airflow.

2.4.2.4 Solving governing equations

Fluid mechanics are governed by Navier-Stokes equations, which describe viscous fluid motion in time and space. These equations can be used in either compressible or incompressible form. Liquids are often modelled to be incompressible. Gases are also often modelled to be incompressible if the velocities are low compared to the speed of sound. Navier-Stokes equations can be solved by using numerical methods for each computational cell. The finite volume method is currently the most used approach in CFD calculations.
The Reynolds number describes the ratio between momentum and viscous forces. As the Reynolds number grows, the flow gradually changes from laminar to turbulent. Currently, Reynolds Averaged Navier-Stokes (RANS) models are the most popular turbulence modelling approach. To calculate turbulence phenomena, RANS models use Reynolds averaging of the velocities, where instantaneous velocity is time averaged to mean the value and fluctuation components around it. For a single velocity component, time-averaged fluctuation around the mean becomes zero. However, for the products of the velocity components, fluctuations create Reynolds stress terms. To solve these, additional equations are required. This problem is known as the turbulence closure problem, which remains a challenge in fluid mechanical studies. Usually, RANS models are based on Boussinesq’s eddy viscosity hypothesis, where Reynolds stresses are modelled as the product of the eddy viscosity and mean shear stresses. Eddy viscosity is assumed to be scalar and a property of the flow. In modelling the eddy viscosity, the most used models are based on two additional transport equations. The most popular of these are k-ε, k-ω and their blended version k-ω SST.

More precise and computationally expensive methods for CFD calculations also exist. Large Eddy Simulation (LES) refers to the turbulence modelling approach, where large length scale eddies are simulated through convolutional filters. For small length scales, sub-grid scale models are typically used for turbulence modelling. The most precise method, Direct Numerical Simulation (DNS), calculates all turbulence phenomena without any additional turbulence model in all length and time scales. The difficulty is that to resolve turbulence phenomena completely, the resolution of temporal and spatial scales has to be high. Therefore, DNS calculations are currently only feasible for moderate Reynolds number flows.

In addition to conventional CFD studies with finite volume methods, Lattice Boltzmann methods (LBM) have been used for nasal airflow studies (Hörschler et al., 2010; Hebbink et al., 2023; Berger et al., 2021b). Lattice Boltzmann calculations approach fluid dynamics from a different perspective than conventional CFD calculations (Perumal & Dass, 2015). In addition, several authors have created an automated pipeline for the CFD studies in Lattice Boltzmann methods. Rüttgers et al. (2022) created a pipeline of automated software for CFD calculations to study nasal cavity geometries with Lattice Boltzmann methods. Berger et al. (2021b) studied the application of Lattice Boltzmann calculations for a pre-surgery planning tool. Shape optimisation was applied to compare virtual surgery with real surgery results, and similar results were observed.
2.5 Nasal airway CFD

In recent years, many nasal airway CFD studies have been published. Using patient imaging information, very detailed three-dimensional information of the nasal cavities can be obtained from nasal airway CFD calculations. The most interesting results from the patient’s perspective usually include the physiologically meaningful flow results at the surfaces of the mucous membrane, where a human being receives flow information. All of these can affect the patient’s subjective sensing of nasal patency and general well-being. In addition, pressure loss along the nasal cavity and nasal resistance ratios can also be obtained, which can affect how difficult it is for the patient to breathe via the nose. This might also translate to a sense of nasal congestion. All these flow variables can be evaluated against the patient’s subjective responses. Although patient cohorts vary between studies, they often include septoplasty patients. Subjective responses are also different between studies but often include a severity of nasal obstruction VAS assessment or quality of life NOSE scores. Quality of life scores are assessed bilaterally for both nasal cavities, whereas VAS assessment can be unilateral or bilateral.

Nasal airway CFD studies are based on imaging information. CT images are acquired in a supine position and CBCT images are acquired in a seating position. Typically, imaging information is obtained without vasoconstriction. Studies usually investigate only inspiratory airflow, since inspiratory airflow is the most difficult for patients. In nasal airflow studies, geometries are usually from the nostrils to the nasopharynx, and the walls of the computational geometry are the surfaces of the mucous membrane. The external nose outside the nasal cavities is not often included in nasal airflow studies. Taylor et al. (2009) studied inspiratory inflow boundary conditions in the nostrils and found the total pressure boundary condition applicable when the external nose is not modelled. Paranasal sinuses can also be included in the calculations, but they have little effect on the results (Xiong et al., 2008).

Boundary conditions aim to model either the daily life conditions of the patient as accurately as possible or specifically some instantaneous conditions in which subjective assessments have been made. The most important boundary conditions of nasal airflow studies are defined primarily with pressure and volume flow rates. Boundary conditions are typically defined bilaterally through both nasal cavities, although the analysis of the CFD results might be conducted unilaterally or locally. Volume flow rates are often defined to be equal to 15 l/min in all conditions or to
be a function of the patient’s gender and weight. Exhaled volume flow rate as a function of gender and weight has been found to be as follows (Garcia et al., 2009):

For males: \[ \dot{V} = (1.36 \pm 0.10) M^{0.44 \pm 0.02} \]

For females: \[ \dot{V} = (1.89 \pm 0.40) M^{0.32 \pm 0.06} \]

where \( \dot{V} \) is flow rate (litres per minute) and \( M \) is weight in kilograms. Steady-state inspiratory or expiratory flow rates used in CFD studies are twice the mean flow rate for each patient defined from Eq. (1).

As an alternative to the flowrate boundary condition assumption, the main boundary condition can be constant pressure drop along the nasal cavities, which can be defined patient specific or equally in all participants. In such cases, volume flow rates form because of the pressure drop and the geometry of the nasal cavities. A typical pressure drop of 15 Pa between the nostrils and the nasopharynx or the nostrils and the choanae is sometimes used to model breathing effort. Alternatively, preoperative and postoperative pressure losses can be defined to be equal and patient specific (e.g., Sullivan et al., 2014; Gaberino et al., 2017, Kimbell et al., 2013; Na et al, 2022). Other typical boundary conditions assume no-slip conditions at rigid and smooth walls. Although surface roughness is rarely considered, Wu et al. (2022) conducted studies with a surface roughness of 0.5 mm in wall functions.

The Womersley number describes transient inertial forces in relation to viscous forces. Therefore, the Womersley number is used when unsteadiness of the fluid motion is evaluated within the nasal cavities. It was originally derived from periodic laminar tube flow (Womersley, 1955). Typically, the Womersley number is small in the nasal cavities, which would approve the use of quasi-steady assumption. However, the findings are controversial about the unsteadiness of the results. Spence et al. (2012) found that unsteadiness is present in the nasal cavity airflow. Furthermore, Hörschler et al. (2010) found that hysteresis phenomena between the accelerating and decelerating phases of breathing is present in nasal flow resistances across the nasal cavities. They used numerical calculations with compressible equations. Groß et al. (2011) suggested that such hysteresis phenomena in rhinomanometric curves are a result of flow storage effect in compressible equations. Cui et al. (2020) studied unsteady flow in the nose and trachea. They found that unsteadiness was more present in the acceleration phase than the deceleration phase. Li et al. (2017) studied various breathing conditions and laminar, RANS models and LES against DNS results for nasal airflow. They
concluded that LES and DNS obtained similar results. At restful breathing, the laminar model corresponded well to DNS calculations. For higher flowrates, however, the k-ω turbulence model obtained the best results against the LES and DNS calculations. However, steady state conditions and incompressibility are usually assumed to be sufficiently precise for practical purposes in most studies. Furthermore, most studies have assumed that laminar flow model is good enough for practical purposes. These approximations are often mentioned, however, as a limitation of the analysis.

Nasal airflow heat transfer calculations are subject to mucosal temperatures and ambient climate conditions. Mucosal temperature and ambient condition assumptions vary, but the constant mucosal temperature is usually close to 32 °C and ambient air temperatures between 20 °C and 25 °C are assumed. In recent years, however, more studies have used assumptions of varying mucosal temperatures in different areas of the nasal cavities (Senanayake et al., 2021; Byun et al., 2019; Kim et al., 2017; Inthavong et al., 2022; Na et al., 2020; Chung & Na, 2021).

In heat and moisture transfer calculations, energy and species transport equations which are subject to boundary conditions, are applied. For moisture transfer, Kumahata et al. (2010) created a two-film model to calculate nasal cavity wall relative humidity and mucosal temperatures. The two-film model was divided on the air side, represented by the computational mesh boundary layer, and on the mathematical model, where the organ and membrane are. At the surface between the organ and the mucous membrane, constant conditions were assumed with 100% relative humidity and a temperature close to core body temperature. For heat transfer, the mucous membrane with an assumed constant thickness formed constant effective heat resistance from the organ to the nasal cavity walls. The mucosal temperature was thereby calculated as a function of heat loss from the organ to airflow and the properties of the mucous membrane. As a result, mucosal temperatures were lower than organ temperatures and changed in different areas of the nasal cavities. Mucosal temperatures obtained by numerical procedure were validated against the measurements on inspiratory airflow by Lindemann et al. (2002).

Many other authors have used a similar approach in steady inspiratory airflow, where an effective resistance is assumed across the mucous membrane with a constant thickness in the whole nasal cavity (Senanayake et al., 2021; Byun et al., 2019; Kim et al., 2017; Inthavong et al., 2022). Although these studies typically assumed organ temperatures quite close to core body temperature of 37 °C, the
effective resistances of the mucous membrane obtained were quite different. For expiratory airflow, a similar approach was also adopted by Na et al. (2020) who obtained a somewhat smaller organ temperature of 33.5°C by first assuming mucous membrane properties. Chung et al. (2021) improved on the work by Na et al. (2020) by studying unsteady breathing during a whole respiratory cycle.

For moisture transfer, many studies have assumed 100% relative humidity at the surface of mucous membrane (Na et al., 2020; Senanayake et al., 2021; Byun et al., 2019; Kim et al., 2017). Latent (i.e. phase change) heat transfer has rarely been analysed or included in energy equations, but some exceptions do exist (Hanida et al., 2013, Na et al., 2022; Inthavong et al., 2022, Kim et al. 2017). Latent heat transfer can be, in some cases, one order of magnitude higher than sensible heat transfer (Kim et al., 2017; Inthavong et al., 2022). Furthermore, the ratio between sensible and latent heat transfer is very sensitive to ambient conditions (Inthavong et al., 2022). However, moisture latent heat transfer has only little additional value in regression analysis against subjective assessments (Na et al., 2022).

Only a few studies exist that include latent heat in the energy equation. Hanida et al. (2013) improved on the calculation procedure of Kumahata et al. (2010) by considering latent heat in the energy equation while also assuming 100% relative humidity at the organ side. While Hanida’s work does not assume fully saturated nasal cavity walls, Inthavong et al. (2022) used the assumption and included latent heat in the energy equation. The inclusion of latent heat transfer inclusion decreased mucosal temperatures, which was in line with the experimental work of Rouadi et al. (1999) in different ambient conditions.

2.5.1 Nasal CFD with subjective assessment

Some CFD studies have been conducted where the subjective assessment of patients has been gathered with NOSE surveys, VAS patency scores or SNOT-22 (Table 2). Few studies, however, also include additional subjective menthol assessments or temperature measurements within the nasal cavities. Indeed, most studies only investigated only inspiratory airflow, since it is considered the most difficult for patients. Studies with pre- and postoperative images have used various follow-up periods, but they are mostly less than one year when reported. Many such studies have used nasal cycle information between images as inclusion or exclusion criteria.
Studies with pre- and postoperative patients have usually assumed pre- and postoperative pressure losses to be equal and thus result in increased flow rates and heat transfer postoperatively, especially from the more obstructed side (Sullivan et al., 2014; Gaberino et al., 2017; Kimbell et al., 2013; Na et al., 2022). Kimbell et al. (2013) used the absence of nasal cycle effects as an inclusion criterion for a nasal airflow study of a cohort of 19 patients. In the study, 10 patients with septoplasty or septorhinoplasty, possibly combined with other operations, were studied pre- and postoperatively. It was found that increased average wall shear stresses and heat fluxes from the most obstructed side improved both unilateral VAS assessment from the same side and NOSE scores. Similarly, decreased nasal resistances and increased airflow improved subjective scores. Small improvements in correlations were also found with nasal resistance ratios and airflow partition ratios compared to absolute values.

In a similar study, Sullivan et al. (2014) studied pre- and postoperative patients. The first 10 patients from a cohort of 40 patients were selected without any obvious nasal cycle changes between pre- and postoperative images. The study investigated surface areas, where certain heat flux thresholds are achieved. The best correlations against subjective assessments were obtained from the surface areas of the most obstructed side, where heat flux exceeds the threshold of 50 W/m² (SAHF50).

Gaberino et al. (2017) used the presence of nasal cycle changes between pre- and postoperative images as an inclusion criterion. From a cohort of 27 patients, 12 patients were selected. It was assumed that those patients were at opposite extremes of the nasal cycle between the pre- and postoperative images. The pre- and postoperative images were then transformed to the mid-cycle images by computational methods (Patel et al., 2015). Correlation coefficients were improved after correcting the nasal cycle effects for NOSE and VAS scores from the most obstructed side. The correlations were reported for total heat transfer, SAHF50, nasal resistances and flowrates from the most obstructed side to the subjective scores. Increased average heat fluxes, and surface areas, where heat flux exceeded 50 W/m², improved subjective patency scores. Further, decreased nasal resistance and higher airflows improved the subjective assessments.
Table 2. Nasal airflow CFD studies with subjective assessments. SD = septal deviation, ITH=inferior turbinate hypertrophy. ENS=Empty Nose Syndrome. NAO = Nasal airway obstruction which include both ITH and SD and their combinations. CT=Simultaneous subjective assessments and CT images. SAHF50=Surface area where heat flux exceeds 50 W/m². HF=Heat flux. f(HF) = function of heat flux. NR = Nasal resistance. MOS = Most obstructed side. Unil. =Unilateral

<table>
<thead>
<tr>
<th>Study</th>
<th>Patient cohort &amp; follow-up time (postop. includes preop.)</th>
<th>Boundary condition</th>
<th>Mucosal &amp; (Ambient if not at 20 °C) temperature</th>
<th>Subjective evaluation</th>
<th>Images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casey et al. (2017)</td>
<td>15 NAO and 15 healthy</td>
<td>15 l/min</td>
<td>32.6 °C</td>
<td>Unil. VAS with covered nostril / NOSE</td>
<td>CBCT</td>
</tr>
<tr>
<td>Gaberino et al. (2017)</td>
<td>12 NAO with postop.</td>
<td>Equal pre- post pressure loss</td>
<td>32.6 °C</td>
<td>Unil. VAS with covered CT nostril / NOSE</td>
<td>CT</td>
</tr>
<tr>
<td>Kimbell et al. (2013)</td>
<td>10 NAO with postop. at 5-8 months</td>
<td>Equal pre- post pressure loss</td>
<td>32.6 °C</td>
<td>Unil. VAS / NOSE</td>
<td>CT</td>
</tr>
<tr>
<td>Malik et al. (2022)</td>
<td>10 SD and 36 healthy</td>
<td>15 Pa</td>
<td>35 °C</td>
<td>Bilat. &amp; Unilat. CBCT VAS/NOSE/SNOT-22</td>
<td></td>
</tr>
<tr>
<td>Na et al. (2022)</td>
<td>8 patients (ITH &amp; SD) with postop. at 3 months</td>
<td>Equal pre- post pressure loss</td>
<td>f(HF) &amp; (25 °C)</td>
<td>NOSE</td>
<td>CT</td>
</tr>
<tr>
<td>Radulesco et al. (2019)</td>
<td>22 SD patients</td>
<td>150 Pa</td>
<td>34 °C &amp; (19 °C)</td>
<td>Unil. nasal congestion</td>
<td>CT</td>
</tr>
<tr>
<td>Sullivan et al. (2014)</td>
<td>10 NAO with postop. at 3-9 months</td>
<td>Equal pre- post pressure loss</td>
<td>32.6 °C</td>
<td>Unil. VAS with covered nostril / NOSE</td>
<td>CT</td>
</tr>
<tr>
<td>Tjahjono et al. (2023)</td>
<td>11 healthy</td>
<td>15 l/min</td>
<td>f(HF)</td>
<td>Unil. VAS / NOSE</td>
<td>CT**</td>
</tr>
<tr>
<td>Zhao &amp; Jiang (2014)</td>
<td>22 healthy</td>
<td>15 Pa</td>
<td>35 °C &amp; (23.6 °C)</td>
<td>Unil. &amp; bilat. VAS / NOSE</td>
<td>CT**</td>
</tr>
</tbody>
</table>
In addition to previous pre- and postoperative studies, Na et al. (2022) studied 8 patients who had undergone bilateral turbinoseptoplasty who had no clear nasal cycle effects present. The study uniquely took moisture transfer with latent heat into account. However, it was also found that moisture transfer does not affect the regression results from sensible heat transfer calculations, although latent heat transfer made, in some conditions, a large contribution to absolute heat transfer. A strong correlation was found between improvements in NOSE scores and an increase in surface heat flux and reductions in nasal resistances from the most obstructed side.

Casey et al. (2017) studied preoperative patients compared with healthy controls. The same flowrates were assumed for all subjects. In addition to the findings of previous studies, it was found that patients with nasal airway obstruction had a deficit in middle region airflow, and increased middle region airflow improved subjective nasal patency. In contrast, Li et al. (2018) studied patients with empty nose syndrome (ENS) compared to healthy controls. All patients had a history of inferior turbinate surgeries possibly combined with other operations. In addition, all patients except one had bilateral symptoms. It was noticed that patients with ENS had a predominant flow in the middle airflow, which left a lower ratio of flow in the inferior region compared to healthy controls. Furthermore, nasal resistances were significantly higher in the healthy cohort compared to patients with ENS.

Radulesco et al. (2019) studied 22 preoperative patients with septal deviation. VAS patency scores were assessed from 0 (no nasal obstruction) to 4 (total obstruction). The definition of less obstructed side (LOS) and most obstructed side (MOS) were based on (instantaneous) assessed patency. It was found that the MOS had smaller heat fluxes but higher air temperatures and higher average wall shear stresses.

Malik et al. (2022) studied 10 patients with nasal septal deviations (SD) against 36 healthy controls. Bilateral and unilateral VAS were collected. A pressure drop of 15 Pa was applied to all subjects as a boundary condition. All subjects were evaluated independently by 2 surgeons. All patients with septal deviations were correctly identified. However, two-thirds of the controls were falsely identified as patients by both surgeons. Those controls falsely identified were grouped as asymptomatic SD, while the rest of the healthy cohort were grouped as non-SD healthy controls. Septal deviation index was similar for symptomatic and asymptomatic SD and different for non-SD healthy controls. In the deviated side
anteriorly from the turbinates, the symptomatic SD group had significantly smaller heat transfer than the other two groups. SAHF50 analysed across the whole nasal cavity, however, was significantly lower in non-SD healthy controls than in the other groups in both the deviated and non-deviated side. Generally, correlations were quite small in any VAS assessments compared to CFD variables. In addition to the CFD calculations, the menthol lateralisation threshold was tested unilaterally. It was observed that symptomatic SD patients had significantly worse capacity to detect menthol. The other groups could detect menthol at 15.2 times lower concentrations than the symptomatic SD group. This might explain the differences in the subjective assessment of nasal patency.

CT images are usually not acquired at the same time as the subjective patency scores. However, exceptions do exist in a few studies with healthy human cohorts which gathered patency scores and CT images at a time point as close as possible (Zhao et al., 2014; Tjahjono et al., 2022). Tjahjono et al. (2022) studied NOSE and (instantaneous) unilateral VAS scores with a healthy cohort. Mucosal temperature boundary condition was calculated as a function of heat loss (Senanayake et al., 2021). Temperature probes were inserted in four locations within the nose and measurements were gathered from both sides of the nasal cavities, resulting in one value at each site. CFD calculations were, however, only conducted in inspiratory airflow. The mucosal temperatures in the measurements and the CFD calculations correlated strongly. Nasal obstruction in VAS scores was associated with higher measured mucosal temperatures and decreased calculated anterior heat transfer in the nasal cavities.

Zhao & Jiang (2014) studied regional peak mucosal cooling with 22 healthy individuals. Unilateral and bilateral VAS assessments were collected twice and averaged for the analysis. Test-retest data were published and a correlation coefficient of 0.75 was obtained. It was found that bilateral subjective nasal patency correlated with peak postvestibule mucosal cooling.

### 2.5.2 Nasal CFD without subjective assessment

In addition to quite rare pre- and postoperative studies with subjective assessments (Table 2), preoperative images can be treated with virtual surgery to ascertain the fluid mechanical effects of surgeries. An exception is a study by Kim et al. (2023) which did not collect subjective assessments but studied septoturbinoplasty with pre- and postoperative images instead. It was assumed that postoperative pressure
loss was equal to preoperative pressure loss, as has been reported in many previous studies with subjective assessments. It was observed that heat transfer across the whole nasal cavity increased postoperatively. Similar results have also been observed in studies with subjective assessments (Table 2).

However, constant flowrate assumption between pre- and postoperative conditions tend to lead to decreased heat transfer postoperatively. Hariri et al. (2015) performed six virtual inferior turbinate surgeries along the whole inferior turbinates in the non-deviated sides for patients with turbinate hypertrophy and septal deviations. Various inferior turbinate surgeries were performed, ranging from mild to aggressive. Nasal heating and humidification decreased because of the surgeries. A similar heat transfer result was observed by Siu et al. (2021) who virtually studied eight patients with nasal airway obstruction in several climate conditions. Preoperative images were compared to virtual bilateral inferior turbinate surgery and virtual total inferior turbinate resection. Chen et al. (2010) also found that virtual bilateral inferior turbinate surgeries reduce heat transfer. Furthermore, Tripathy et al. (2023) studied patients with septal deviations and performed virtual septoplasty surgery. Here, it was also found that heat transfer decreased postoperatively. However, relative humidity increased postoperatively for most patients, although moisture transfer did not.

Turbinate surgeries can be performed to different extents and in various sites of the turbinates. Lee et al. (2018) performed six virtual inferior turbinate reductions for each CT scan with a fixed pressure loss of 15 Pa. Bilateral surgeries were performed in several different sites of the inferior turbinates divided into three thirds, from anterior to posterior and their combinations. For each patient, it was found that nasal flowrates and nasal turbinate volumes had high correlations.

Adhesions are often seen postoperatively after septoplasty or turbinate reduction. Senanayake et al. (2021) studied virtual nasal adhesions at various sites within the nasal cavities and their effects on nasal airflow. Although localised downstream disruptions of the nasal airflow with decreased mucosal heat transfer were observed, the adhesions did not significantly change overall nasal airflow.

Borojeni et al. (2022) studied healthy subjects and reported normative ranges for unilateral airflow heat flux and flow resistances. Strong correlations between unilateral airflow and inferior and middle airflow were found. However, in comparison, superior airflow and unilateral airflow had weaker correlations. Brüning et al. (2020) created statistical shape models of a healthy cohort and found that highest wall shear stresses were concentrated in the nasal valve area. The highest velocities of the nasal cavities were also found in the nasal valve region in a
nasal valve phenotype study (Inthavong et al., 2019). Jin et al. (2023) studied the influence of nasal vestibule structure on nasal obstruction using CFD calculations and machine learning. In machine learning, classification of two groups was performed. The groups were separated by their response to the use of anterior rhinoscopy. The classification task obtained good results by using anatomical features.

Studies of nasal airflow are primarily conducted without decongestion. However, Xiao et al. (2021) studied the effects of decongestion with healthy subjects. CT images with and without decongestant were acquired. On average, decongestion increased the cross-sectional area of the nasal cavity in the turbinates by 1.4 times. The cross-sectional perimeter was, however, only marginally altered, so the Reynolds number did not change after applying decongestant. In addition, flow resistances were reduced by 50% when decongestant was applied, the majority occurring in the posterior nasal cavity. Although decongestion exposes more of the superior nasal cavity, a smaller portion of the flow was found to reach this area due to concomitant reduction of the inferior turbinate region. It was also observed that deviations in the cross-sectional areas and resistances decreased after applying decongestant.

Olfactory function can also be studied in addition to nasal obstruction. Alam et al. (2019) studied the impact of bilateral middle turbinectomy on olfactory cleft and nasal airflow. Virtual middle turbinate operations were performed on five preoperative models, and a constant pressure drop of 15 Pa was applied between the nostrils and the nasopharynx in all models. It was noticed that nasal resistances decreased and volume flow rates increased postoperatively. The olfactory cleft results were equivocal due to anatomic differences. Wu et al. (2022) also studied olfactory function in healthy subjects and found that airflow, airflow velocity and airflow ratio were highly positively correlated with subjective olfactory function. Sicard et al. (2021) studied olfactory function with different nasal vestibules on healthy subjects. They found that the same nasal vestibule phenotypes produced similar olfactory airflow rates. Nishijima et al. (2018) studied the effect of nasal polyp location on olfactory function. In their study, they found that nasal polyp location affects olfactory airflow.
2.5.3 CFD compared to rhinomanometry results

Several studies have analysed patients’ active anterior rhinomanometry results with CFD calculations. Compared to rhinomanometry, CFD tends to underpredict nasal airflow resistances in many conditions (Schmidt et al., 2022; Radulesco et al., 2019; Cherobin et al., 2021; Berger et al., 2021a; Osman et al., 2016). Radulesco et al. (2019) found that inspiratory nasal airflow resistance in rhinomanometry for the MOS was 1.8 ± 2.2 [Pa*s/cm$^3$] and 0.6 ± 0.37 [Pa*s/cm$^3$] for the LOS, while CFD calculated resistances for the MOS were 0.8 ± 1.17 [Pa*s/cm$^3$] and 0.23 ± 0.1 [Pa*s/cm$^3$] for the LOS at a transnasal pressure drop of 150 Pa. Berger et al. (2021a) studied active anterior rhinomanometry against Lattice Boltzmann CFD calculations at a transnasal pressure drop of 150 Pa. They found that in the LOS, CFD seems to obtain similar results as active anterior rhinomanometry. For the MOS, however, error rates of up to 100% were observed. No differences were observed between expiratory and inspiratory underpredictions.

Cherobin et al. (2021) studied rhinomanometry against CFD calculations after applying decongestant to remove nasal cycling effects at a transnasal pressure drop of 75 Pa. As in other studies, the ratios between rhinomanometric and CFD results were closer to equal at high nasal airflows, whereas lower flowrates obtained more underprediction by the CFD. The rhinomanometric nasal resistance mean coefficient of variability was also reported, which was 12 ± 13%.

Schmidt et al. (2022) studied active anterior rhinomanometry with two rhinomanometric devices and obtained similar results between the two devices at a transnasal pressure drop of 75 and 150 Pa. Lower flowrates obtained more underprediction by CFD than high flowrates. There was no difference between underpredictions by expiratory or inspiratory airflow, which does not explain the tissue movements behind the underpredictions by CFD. According to Schmidt et al., the systematic underprediction by CFD remains an elusive problem.
3 AIMS OF THE STUDY

Aims of the study are as follows:

1) To investigate how 3D printing could be used to replicate the nasal cavities and the airflow passing through them from a clinical viewpoint. (I)

2) To ascertain how well PIV measurements could serve as CFD model validations for nasal airflow. (II)

3) To investigate and compare how 3D volumetric measurements and cross-sectional area measurements taken from CBCT scans correlate with subjective assessments. (III)

4) To demonstrate how CFD simulations can reveal airflow changes in the anterior parts of the inferior turbinates caused by surgical interventions, and to investigate how the subjective symptom responses of patients correlate with objective nasal airflow CFD. (IV-V)
4 MATERIALS AND METHODS

4.1 Patient selection (I-V)

Those patients selected for the studies had chronic nasal congestion symptoms as their main rhinological condition and underwent inferior turbinate surgery. Patients had a positive response to vasoconstriction but not with longer term nasal steroids. Those patients who had at least a 30% increase in nasal airway volumes in both the right and left nasal cavities V2-5 after applying xylometazoline in acoustic rhinometry were included in the studies. All other patients were excluded. All images and rhinomanometric information in the studies were, however, gathered without xylometazoline. Further exclusion criteria included chronic rhinosinusitis, nasal polyps, septal deviations and tumours. Five preoperative patients were randomly selected from the cohort for plastic 3D prints (I). Both sides of the nasal cavities were then analysed for each patient. The experimental silicone model used for the PIV the measurement was constructed from the randomly selected preoperative CBCT scans of the patients (II).

To study the effect of RFTA treatment, 26 patients underwent inferior turbinate surgery. Prior to surgery, all patients had enlarged inferior turbinates on both sides of the nasal cavities, which were subsequently treated with RFTA in a similar operation. CBCT images and acoustic rhinometry results were collected for all patients preoperatively and at twelve months postoperatively. One patient was excluded from further study due to extensive artefacts from dental fillings. This left 25 patients in the study. In addition, one patient was excluded from the correlation analyses because acoustic rhinometry was missing. Thus, 24 patients were included in the correlation analysis and 25 patients for other analyses. (III)

In a pilot study, 8 patients selected from the extremes of subjective and objective responses were selected from an inferior turbinate surgery cohort of 25 patients with CBCT images (IV). To study the correlation between CFD calculations from CBCT scans and acoustic rhinometry and subjective assessments, 25 patients who were undergoing inferior turbinate surgery were studied pre- and postoperatively (V).
4.2 CBCT scans (I-V)

CBCT was used pre- and postoperatively for patient imaging in the cohort, as CBCT exposes patients to a relatively lower dose of radiation than conventional CT. For CBCT imaging, the Scanora 3Dx (Soredex, Inc., Tuusula, Finland) and the Planmeca Max (Planmeca, Helsinki, Finland) were used. The following imaging parameters were used: 0.2 mm CT slice thickness, voxel size 0.2 mm, 90 kVp, 8 mA and 4 s radiation time. After imaging, the CBCT data were saved in Digital Imaging and Communications in Medicine (DICOM) format. The images used were taken from the databases of Tampere University Hospital.

4.3 3D printing and construction of silicone model for PIV measurements (I-II)

The CBCT scans of five preoperative patients were selected for the 3D printing of the nasal cavities using PLA filament. All paranasal sinuses were also included. MATLAB software (MathWorks, Inc., Natick, Massachusetts, United States) was used to process the DICOM images of the five preoperative patients for 3D printing of the nasal cavities. The data were saved in Standard Tessellation Language (STL) format for the 3D printing. Before printing, the STL models were processed with 3D open-source modelling Blender software (The Blender Foundation) to fix any possible errors in the models. (I)

The plastic 3D prints were produced on a Lulzbot Taz 4 3D printer (Aleph Objects, Inc., Loveland, Colorado, United States) using the Fused Deposition Modelling (FDM) technique. In FDM printing, the raw material is deposited through a print head. Polylactic acid (PLA) was used as the raw material.

The plastic 3D prints were printed from the level of the nasopharynx to the level of the frontal sinus in 1:1 size. No supporting structures were generated for the 3D prints. However, some printing artefacts were left in the cavities after printing due to the lack of supporting structures. After 3D printing, CBCT images were acquired of each print for further analysis and to confirm that the prints corresponded to the data of the real patients.

In addition to the plastic 3D prints (I), one silicone model of the nasal cavities was created (II). The procedure used for constructing the silicone model of the nasal cavities to be used in the PIV measurements closely followed the approach previously presented by Hopkins et al. (2000). Preoperative nasal CBCT scans of
one adult patient were used. CBCT data were downloaded to OnDemand3D™ software (version 1.0, CyberMed, Inc., Yuseong-gu, Daejeon, South Korea). The bilateral pneumatized volume of the nasal cavities was isolated from the CBCT scans. We included the structures in the nasal cavities from the nostrils to the nasopharynx, excluding the paranasal sinuses. OnDemand3D™ software was then used to form a 3D image of the pneumatized volume of the nasal cavities based on HU values. After this, the 3D image data were saved into Standard Tessellation Language (STL) file format for printing. Small artefacts were later removed from the STL files using the Blender software.

The STL files were scaled by a factor of 1.85 to create a more convenient setup for in vitro PIV measurements. Based on the STL files, a negative of the nasal cavity (Figure 5) was printed in water-soluble filament polyvinyl alcohol (PVA) with the 3D printer Ultimaker 2.0 (Ultimaker B.V., Netherlands).

![Figure 5. The printed negative of the nasal cavities used for the silicone model. Scaling of 1.85. (II)](image)

Negatives of the nasal flow passages were printed in several different parts. The combined printing time of the nasal passages was approximately 57 hours. The merging of the different parts was made with screws and water-soluble glue. The
printed PVA negative of the nasal cavity was positioned in a Plexiglas box. Then, uncurred Dow Corning Sylgard 184 (Dow Corning, USA) silicone was used to cover the printed nasal cavities inside the Plexiglas box. The box was then positioned in a vacuum chamber to ensure the removal of air bubbles and dissolved air. The removal of PVA was done with 55 °C water. The correct CFD model geometry was ensured by also acquiring CBCT scans from the produced silicone model. Thus, the same nasal cavity model was used in the CFD studies as in the PIV measurements.

4.4 CFD calculations (II, IV-V)

A laminar model and k-ω and k-ω SST turbulence models were used and compared with each other. All the calculations were made with water-glycerine mixture flow properties, as was the corresponding experimental work in the PIV silicone model. (II) Based on the results, later studies used the laminar flow model as an approximation in airflow studies. The material properties of air were considered constant in all conditions. Heat conductivity was 0.0256 W/mK, dynamic viscosity 1.8*10^{-5} kg/(m*s) and density 1.2 kg/m^3. Ambient air had a temperature of 20 °C. (IV-V) All calculations used incompressible flow approximation and assumed stationary boundary conditions. (II, IV-V)

All CFD calculations were performed with OpenFOAM 5.0 software. Computational meshes were generated with OpenFOAM utilities blockMesh and snappyHexMesh. Calculations were made with static images with no-slip conditions at the walls. Second-order discretization schemes were used with linear upwind scheme for divergence terms. The highest y+ values at the walls remained roughly at unity and no wall functions were used. Nasal cavities were modelled without external nose. Thus, inspiratory flow was not disturbed outside the nasal cavities and the total pressure boundary condition in the nostrils was deemed sufficient. Volume flowrate was defined at the outlet downstream from the nasopharynx. Calculations were parallelised for 24 processors. Mesh independence was studied with different mesh sizes in the PIV experiment geometry (Figure 6, II). Based on these results, later airflow studies used 4-6 million cells in all calculations to reach grid independence (IV-V).
Figure 6. Mesh independence study based on area averaged pressure differences between the nostrils and the fourth cross-section of the silicone model as a function of mesh size. (II)

No heat transfer was present in the water-glycerine mixture flow PIV experiments, nor in the calculations (II). Airflow studies had heat transfer present from the mucous membrane. Mucosal heat transfer was calculated with the following equation (IV-V):

\[ q = h_m (T_{\text{body}} - T_{\text{mucous}}) \]  \hspace{1cm} (2)

where \( q \) is a local heat flux (W/m\(^2\)) from the mucous membrane surface to airflow; \( T_{\text{body}} \) is body temperature of 310.15 Kelvin (K); \( T_{\text{mucous}} \) is local mucous membrane surface temperature and \( h_m \) is a uniform heat transfer coefficient across the mucous membrane in all positions of the nasal cavities. The coefficient \( h_m \) was experimentally adjusted to 50 W/(m\(^2\)K) to ensure similar mucous membrane surface temperatures as in the clinical measurements by Lindemann et al. (2002).
4.5 Subjective assessment of nasal patency (III-V)

Patients were asked to fill out the VAS and GHSI questionnaires for the previous 7 days at the time of inspection, both pre- and postoperatively. The patients were asked to fill out the VAS questionnaire to simultaneously evaluate the severity of the nasal obstruction on both sides of the nasal cavities on a scale of 0 to 10, with 0 meaning completely open and 10 completely blocked. Furthermore, to assess Quality of life (QOL), patients were also asked to fill out the GHSI questionnaire, which contains 18 questions measured with a 5-point Likert scale. The scores are then transformed to a scale ranging from 0 to 100. Higher scores in the GHSI indicate an enhancement in patient well-being and QOL.

4.6 Measurements of 3D nasal prints (I)

The volumetric measurements of the pneumatised volumes in the patients’ nasal cavities and maxillary sinuses were measured from the patients’ CBCT scans and by using Hounsfield unit (HU) thresholds for in vitro 3D nasal print scans. All paranasal sinuses were excluded from the measurements except for the maxillary sinuses, which were measured separately. Volumetric measurements were evaluated from all CBCT scans using OnDemand3D (version 1.0, CyberMed, Inc., Yuseong-gu, Daejeon, South Korea). The volumetric software (OnDemand3D) used in our study included some excess structures in the areas of the volumetric measurements despite the defined values. These structures were manually excluded. In addition, linear measurements were made in septum length, nasal cavity height and width of the nasal cavity.

Rhinomanometric measurements were done by active anterior rhinomanometry with an NR6 rhinomanometer (GM Instruments Ltd, Kilwinning, Scotland, United Kingdom) for both the patients and the in vitro 3D plastic prints. The airflow in the in vitro 3D plastic prints was produced by one of the investigators breathing through a plastic tube connected to the nasopharynx of the 3D prints. The results were obtained using the well-known Broms’ method. One patient was excluded from the rhinomanometry data analysis due to failed measurements.

All the measurements were performed to compare the results in vivo and in vitro. We observed a small difference in volumetric and linear measurements between the patient and the plastic 3D model. Therefore, as an additional analysis, we also used a scaling formula to make the rhinomanometric results in vitro
comparable with the results in vivo. An analogy was assumed from the laminar tube flow Hagen-Poiseuille equation by taking into account nasal cavity volumes and septum lengths. The geometric mean was used in presenting the rhinomanometric results.

4.7 PIV performance in validating CFD models on nasal cavity CBCT scans (II)

CBCT images were acquired from the silicone model. All the PIV experiments and corresponding CFD calculations were conducted on this model with a water-glycerine mixture flow. Every position in the PIV measurement domain of the silicone model was measured with 5 series, each consisting of 100 double-frame images. In all measurements, the time delay between the double-frames remained at 1 ms, while consecutive double-frame images were gathered at 10 Hz. It was assumed that seeding particles scattered in the liquid mixture followed the flow field perfectly. On average, one whole horizontal cross-section was measured in one working day.

An inspiratory airflow rate of 10 l/min in vivo was studied. By Reynolds number matching between in vivo and in vitro conditions, this corresponded to 13.53 l/min under in vitro conditions. The PIV measurements obtained instantaneous flow fields in two dimensions, which corresponded to the longitudinal and vertical axis of the nasal cavities of the patient. The velocities of the two obtained components were considerably higher than that of the unobtained velocity component in most regions of the measurement domain.

In data analysis, time averaged axial mean flow velocity and axial volume flow rate ratios were measured from PIV experiments and calculated from CFD in four cross-sections. Four coronal cross-sections were chosen for the data analysis between the CFD and PIV calculations: the anterior tip of the inferior turbinate, the anterior tip of the middle turbinate, the posterior part of the inferior turbinate and the nasopharynx. The first three coronal cross-sections of the nasal cavity were divided into three vertical parts and further divided into left and right sides to better illustrate the route of the flow. The fourth cross-section was only divided into left and right sides. (Figure 7)

Axial volume flow rate ratios were calculated by dividing local flow rates over summarised total flow rates. The numerical post-processing was made with the open-source visualisation and data analysis software ParaView 5.0.1.
Figure 7. Study geometry for PIV experiments. The coronal planes in blue represent analysis cross-sections. The horizontal planes in red vertically divide the study geometry into three parts.

4.8 3D measurements in assessing the results of the inferior turbinate surgery (III)

The pre- and postoperative CBCT scans of 25 patients were used to virtually create a 3D model of the inferior turbinates for volumetric measurements using OnDemand3D. The measurements were conducted for the operated anterior part of the inferior turbinates and the surrounding air space on both sides of the nasal cavities. The anterior part consisted of an area 5 mm to 20 mm posterior from the anterior peak of the inferior turbinate. Some 3D modelling artefacts were manually excluded.

In addition, coronal cross-sectional areas from both the inferior turbinates and the air spaces surrounding the inferior turbinates were measured. The
measurement of the cross-sectional areas started 5 mm and ended 50 mm posterior from the anterior peak of the inferior turbinate. The distance between each measuring point was 5 millimetres.

The uppermost limit of the region of interest (ROI) for both the volumetric cross-sectional area measurements was set at the lowest level of the middle turbinates. The lower limit of the ROI was set at the nasal cavity floor. Acoustic rhinometry tests without vasoconstriction and the results V2-5 were included in the study. The volumetric and cross-sectional area measurements were compared to the patients’ subjective nasal patency VAS and QOL (GHSI) scores.

4.9 CFD calculations in inferior turbinate surgery (IV-V)

To study the airflow in the nasal cavities, we used a constant inspiratory flow rate that was also patient specific by determining the flow rate as a function of gender and weight (Garcia et al., 2009)

\[
\dot{V} = (1.36 \pm 0.10)M^{0.44\pm0.02}
\]

For females:

\[
\dot{V} = (1.89 \pm 0.40)M^{0.32\pm0.06}
\]  \hspace{1cm} (3)

where \(\dot{V}\) is flow rate (litres per minute) and \(M\) is weight in kilograms. The steady-state inspiratory flow rates used in the calculations were twice the mean flow rate for each patient defined from Eq. (3).

Total heat transfer and magnitudes of wall shear forces were calculated at the surface of the mucous membrane in the operated anterior parts of the inferior turbinates. The anterior part consisted of a 5 to 20 mm area posterior from the anterior peak of the inferior turbinate (Figure 8). The uppermost limit of the inferior turbinates was set at the lowest level of the middle turbinates. All values were then integrated separately into total values in the operated anterior 5 mm to 20 mm parts of the inferior turbinates. (V)
Furthermore, natural logarithms of heat transfer variables were calculated locally at the surface of the mucous membrane in the same regions and integrated to the total values. This calculation stems from the assumption that the patients’ perceived local sensation to flow variable stimuli is logarithmic and is, therefore, in accordance with the classic Weber-Fechner law. Further, in these calculations, it was assumed that perceived local sensation is non-existent, as flow variables are locally zero. The following equations were used to calculate local Weber-Fechner values:

\[
q_L = \ln(a \cdot q + 1)
\]

where \(q_L\) is Weber-Fechner wall heat flux, \(q\) is heat flux in Watts [W] and \(a=1\) is experimental coefficient.

Pressure losses along the nasal cavities were calculated from the nostrils to the nasopharynx to assess the total effects of the inferior turbinate surgeries. Nasopharynx results were measured vertically at the bottom level of the inferior turbinates airways, as not all patients had much downstream geometry from the nasopharynx. In all our calculated cases, our mesh geometry was extended 50 mm downstream from the nasopharynx for computational reasons. The analysis was...
made to both sides of the nasal cavities simultaneously as was the treatment and patient VAS questionnaire and the GHSI assessment. The Wilcoxon signed-rank test was used to analyse the statistical significance of the results between the pre- and postoperative conditions. Spearman’s rank correlation was used to analyse univariate correlations between all results. The numerical post-processing of the acquired CFD data was performed with the open source visualisation and data analysis software ParaView 5.0.1.

4.10 Ethics

In studies I-II, patient material was collected from the database of Tampere University Hospital. In studies III-V, the study protocols were approved by the Ethics Committee of Pirkanmaa Hospital District. All studies were ethical and based on previously collected patient CBCT imaging information, and therefore no additional radiation doses were received.

4.11 Statistics

As the in vitro studies had experimental design, no statistical analyses were conducted due to small sample sizes (I-II). Statistical analyses were made between the pre- and postoperative changes and respective Wilcoxon statistics were calculated (III-V).
5 RESULTS

5.1 Measurements of 3D nasal prints (I)

In the 10 volumes of the maxillary sinuses, the results in vivo were higher with a ratio of 1.05 ± 0.01 (mean ± SD) compared with the volumetric results in vitro (Table 3).

<table>
<thead>
<tr>
<th></th>
<th>Maxillary sinuses (cm³)</th>
<th>Nasal cavities (cm³)</th>
<th>Nasal septum length (mm)</th>
<th>Nasal cavity height (mm)</th>
<th>Nasal cavity width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In vivo</strong></td>
<td>17.9 ± 4.0</td>
<td>15.9 ± 3.8</td>
<td>82.6 ± 5.2</td>
<td>45.1 ± 2.4</td>
<td>18.7 ± 5.2</td>
</tr>
<tr>
<td><strong>In vitro</strong></td>
<td>17.1 ± 3.9</td>
<td>13.4 ± 4.1</td>
<td>80.5 ± 5.3</td>
<td>43.5 ± 2.3</td>
<td>17.8 ± 5.5</td>
</tr>
<tr>
<td><strong>Comparison</strong></td>
<td>1.05 ± 0.01</td>
<td>1.20 ± 0.1</td>
<td>1.03 ± 0.02</td>
<td>1.04 ± 0.03</td>
<td>1.06 ± 0.1</td>
</tr>
</tbody>
</table>

In the 10 nasal cavities, the volumetric measurements were higher in vivo with a ratio of 1.20 ± 0.1 (mean ± SD) when compared with the results in vitro. In the 5
linear measurements, the results were slightly higher in the measurements in vivo. (Table 3)

In rhinomanometric results, the 10 unilateral rhinomanometry resistances were less in inspiration than in expiration. The resistance in vivo was less in inspiration with a geometric mean ratio of 0.77 and in expiration with a ratio of 0.71. (Table 4)

<table>
<thead>
<tr>
<th></th>
<th>Inspiration resistance GM (GSD)</th>
<th>Expiration resistance GM (GSD)</th>
<th>Total inspiration resistance GM (GSD)</th>
<th>Total expiration resistance GM (GSD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In vivo</strong></td>
<td>0.58 (2.21)</td>
<td>0.61 (2.37)</td>
<td>0.23 (1.25)</td>
<td>0.24 (2.43)</td>
</tr>
<tr>
<td><strong>In vitro</strong></td>
<td>0.76 (2.96)</td>
<td>0.87 (2.70)</td>
<td>0.28 (2.56)</td>
<td>0.33 (2.35)</td>
</tr>
<tr>
<td><strong>Comparison</strong></td>
<td>0.77 (2.60)</td>
<td>0.71 (2.20)</td>
<td>0.81 (2.21)</td>
<td>0.71 (1.68)</td>
</tr>
<tr>
<td><strong>In vitro (scaled)</strong></td>
<td>0.52 (2.89)</td>
<td>0.59 (2.65)</td>
<td>0.20 (2.62)</td>
<td>0.24 (2.43)</td>
</tr>
<tr>
<td><strong>Comparison (scaled in vitro)</strong></td>
<td>1.13 (2.64)</td>
<td>1.04 (2.24)</td>
<td>1.14 (2.30)</td>
<td>0.99 (1.78)</td>
</tr>
</tbody>
</table>

When the results in vitro were scaled based on differences in nasal cavity volume and septum length, the similar ratios were 1.03 and 0.95 with geometric standard deviation factors of 2.86 and 2.39, respectively. The total resistance results obtained with rhinomanometry were analogous to the unilateral measurement results. (Table 4)
5.2 Assessment of PIV performance in validation of CFD models (II)

Axial mean flow velocities calculated from laminar CFD showed the highest results in the left nasal cavity’s lower third in the first cross-section and in the middle third in the second cross-section. This corresponded with the PIV measurements. In the right nasal cavity, the calculated axial mean flow velocities in laminar CFD were highest in the lower third of the first cross-section and in the lower third of the third cross-section (Figure 9). The CFD calculations corresponded with the PIV measurements. The differences in axial mean velocities between the laminar and turbulent (k-ω and k-ω SST) CFD models were small.

![Figure 9](image.png)

**Figure 9.** The velocities in the four analysed coronal cross-sections. The smallest values are presented in violet and the highest in yellow. a.) Axial mean flow velocities (m/s) from laminar CFD results. b.) Axial mean flow velocities (m/s) from PIV measurements. (II)

5.3 3D evaluation of volumetric measurements due to inferior turbinate surgery (III)

When the preoperative and postoperative measurements were analysed together and pooled (n=48), the volumetric measurements of the pneumatised nasal cavity in the anterior part of the measured region correlated with acoustic rhinometry V2-5 and with VAS scores (Figure 10). Turbinate volume also correlated with VAS and QOL scores in the anterior parts of the measured region.
Figure 10. Correlation graphs for the 3D volumetric measurements of the individual anterior parts of the inferior turbinates (n = 48). The air volume (cm$^3$) correlations between VAS score and V2-5 are presented in graphs A and B. The turbinate volume correlations between VAS and QOL scores are presented in graphs C and D. Spearman’s rho number and correlation line are included in the graphs. (III)

The main changes in cross-sectional area from pre- to postoperative measurements were found in the region of the operated anterior part of the inferior turbinate and the pneumatised area surrounding it (Figure 11). The changes were also statistically significant. Some smaller cross-sectional area changes of statistical significance were also found in the posterior regions of the inferior turbinate.
Figure 11. Cross-sectional area changes in both inferior turbinate (conchae) and surrounding air in every measuring point (n = 25). The results have been calculated from the median total cross-sectional area measurements. The distance represents the measuring point distance from the anterior peak of the inferior turbinate. Statistically significant changes are marked with asterisks (** for p < 0.01 and * for p < 0.05). (III)

5.4 Flow variable correlations to subjective assessment of nasal patency (IV-V)

In the anterior 5 mm to 20 mm of the inferior turbinates, statistically significant decreases were found in total wall shear forces (p<0.01) between the pre- and postoperative conditions (n=25). For heat transfer, it has been observed that logarithmically transformed Weber-Fechner heat transfer increased postoperatively, whereas heat transfer itself decreased postoperatively. (Table 5)
Table 5. Computational fluid dynamics result changes for all patients (n=25). Changes in CFD values are calculated by subtracting the preoperative values from 12-month postoperative values. Both sides of the nasal cavities are analysed together. Inferior turbinate (IT) results are presented in the anterior parts (5 mm to 20 mm) of the inferior turbinates and outside from the rest of the nasal cavities. Logarithmically transformed Weber-Fechner (W-F) results are also presented for heat transfer. The Wilcoxon signed-rank test was used to calculate two-sided p-values. WSF=wall shear forces. HT=heat transfer. (V)

<table>
<thead>
<tr>
<th></th>
<th>In the anterior parts of the inferior turbinates</th>
<th>Outside of the anterior parts of the inferior turbinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>-1.12*10^-4</td>
<td>-0.05</td>
</tr>
<tr>
<td>(IQ25-IQ75)</td>
<td>(-2.5<em>10^-4, -6.0</em>10^-6)</td>
<td>(-0.13, 0.03)</td>
</tr>
<tr>
<td>Change p-value</td>
<td>&lt;0.01</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Pressure loss results from ambient to nasopharynx are presented in Table 6 for all 25 patients. No statistical significance was found in pressure loss changes from ambient to nasopharynx between pre- and postoperative conditions. Furthermore, pressure loss median results for 4 subgroups are also presented (IV).
Table 6. Pressure loss (Pa) from ambient to nasopharynx for all patients (n=25) pre- and postoperatively and for subgroups (Gr. 1-4), each consisting of 2 subjects from the extremities of subjective and objective volumetric responses. Subgroups 1-2 have high VAS changes and subgroups 1 and 3 have high volumetric changes (IV). All changes are calculated by subtracting preoperative values from 12-month postoperative values. The geometric mean of ratios between pre- and postoperative pressure losses were calculated for all patients. The statistical significance of the change between pre- and postoperative results was analysed with Wilcoxon signed-rank test.

<table>
<thead>
<tr>
<th></th>
<th>Preop. (Pa)</th>
<th>Median (IQ25-IQ75) 23.2 (18.5-36.1)</th>
<th>Median preop. in groups 1-4 ( 74.4 / 30.7 / 17.4 / 20.9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Postop. (Pa)</td>
<td>Median (IQ25-IQ75) 20.0 (12.3-27.8)</td>
<td>Median postop. in groups 1-4 ( 12.8 / 37.7 / 11.9 / 31.9 )</td>
</tr>
<tr>
<td>Changes (Pa)</td>
<td>Median (IQ25-IQ75) -2.3 (2.3-(-10.6))</td>
<td>p-value 0.1936</td>
<td></td>
</tr>
</tbody>
</table>

Post/Pre ratio in geometric mean (n=25)

0.76

In the anterior parts of the inferior turbinates, a statistically significant negative correlation was found between total wall shear force values (p<0.001) and volumetrically measured airway volumes (n=50) when all values were pooled. (V) In the same area, a statistically positive significant correlation was found between logarithmically transformed Weber-Fechner heat transfer and volumetrically measured airway volumes (p<0.05) and acoustic rhinometry V2-5 cm results (p<0.01). (Table 7)
### Table 7

Univariate Spearman correlations between calculated CFD values in total wall shear forces (WSF) and total heat transfer (HT) and its’ logarithmically transformed Weber-Fechner heat transfer values from the anterior 5 mm to 20 mm parts of the inferior turbinates and the subjective and objective measures. Both sides of the nasal cavities are analysed together. Table 7 also presents p-values (n=50), acoustic rhinometry results V2-5 cm were missing for one patient (n=48). (V)

<table>
<thead>
<tr>
<th></th>
<th>VAS and</th>
<th>GHSI and</th>
<th>V2-5 and</th>
<th>Air volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WSF</td>
<td>HT</td>
<td>WSF</td>
<td>HT</td>
</tr>
<tr>
<td>Spearman’s rho</td>
<td>0.19</td>
<td>0.17</td>
<td>-0.08</td>
<td>-0.01</td>
</tr>
<tr>
<td>p-value</td>
<td>0.18</td>
<td>0.24</td>
<td>0.56</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Weber-Fechner transformed values in heat transfer and

<table>
<thead>
<tr>
<th></th>
<th>VAS</th>
<th>GHSI</th>
<th>V2-5</th>
<th>Air volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spearman’s rho</td>
<td>-0.02</td>
<td>0.06</td>
<td>0.43</td>
<td>0.33</td>
</tr>
<tr>
<td>p-value</td>
<td>0.90</td>
<td>0.68</td>
<td>&lt;0.01</td>
<td>0.02</td>
</tr>
</tbody>
</table>

In the anterior parts of the inferior turbinates, a statistically significant negative correlation was found between total wall shear force value and volumetrically measured air volume changes (n=25) between the pre- and postoperative conditions (p<0.001). For patients’ subjective assessment, there was a statistically significant positive correlation in the anterior parts of the inferior turbinates.
between total wall shear force changes and nasal obstruction VAS changes (p=0.04). No other statistically significant results were found between total wall shear force or heat transfer changes and changes in nasal obstruction VAS or GHSI. (V) (Table 8)

Table 8. Univariate Spearman correlations between changes in calculated CFD values (total wall shear forces and total heat transfer) and its’ logarithmically transformed Weber-Fechner heat transfer values from the anterior 5 mm to 20 mm parts of the inferior turbinates and changes in subjective and objective measures. Changes in CFD values are calculated by subtracting preoperative values from 12-month postoperative values. Both sides of the nasal cavities are analysed together. Table 8 also presents p-values (n=25). Acoustic rhinometry results V2-5 cm were missing for one patient (n=24). (V)

<table>
<thead>
<tr>
<th></th>
<th>VAS and WSF</th>
<th>GHSI and WSF</th>
<th>V2-5 and WSF</th>
<th>Air volume WSF</th>
<th>VAS and HT</th>
<th>GHSI and HT</th>
<th>V2-5 and HT</th>
<th>Air volume HT</th>
<th>Spearman’s rho</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.40</td>
<td>-0.19</td>
<td>-0.24</td>
<td>-0.65</td>
<td>0.25</td>
<td>0.06</td>
<td>0.12</td>
<td>-0.36</td>
<td>0.04</td>
</tr>
<tr>
<td>p-value</td>
<td>0.04</td>
<td>0.38</td>
<td>0.27</td>
<td>&lt;0.001</td>
<td>0.23</td>
<td>0.77</td>
<td>0.58</td>
<td>0.08</td>
<td></td>
</tr>
</tbody>
</table>

Weber-Fechner transformed values in heat transfer and subjective measures

<table>
<thead>
<tr>
<th></th>
<th>VAS</th>
<th>GHSI</th>
<th>V2-5</th>
<th>Air volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spearman’s rho</td>
<td>0.04</td>
<td>-0.06</td>
<td>0.32</td>
<td>0.07</td>
</tr>
<tr>
<td>p-value</td>
<td>0.83</td>
<td>0.77</td>
<td>0.12</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Further, no statistically significant correlations were found between pressure losses from ambient to nasopharynx (n=50) and their changes (n=25) between the pre- and postoperative conditions and subjective nasal obstruction VAS and GHSI measures. However, a statistically significant positive correlation was found between pressure loss changes (n=25) along the nasal cavity and total wall shear force value changes in the operated parts of the inferior turbinates between the pre- and postoperative conditions (p<0.001). (V) (Table 9)

<table>
<thead>
<tr>
<th></th>
<th>Pressure loss from ambient to nasopharynx and</th>
<th>Changes in pressure loss from ambient to nasopharynx and changes in</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VAS (n=50)</td>
<td>GHSI (n=50)</td>
</tr>
<tr>
<td>Spearman’s rho</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>p-value</td>
<td>0.86</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Table 9. Univariate Spearman correlations between calculated CFD pressure loss from ambient to nasopharynx and subjective measures and total wall shear forces (WSF) in the anterior 5 mm to 20 mm parts of the inferior turbinates. Changes in CFD values are calculated by subtracting preoperative values from 12-month postoperative values. Both sides of the nasal cavities are analysed together in the WSF results. Table 9 also presents p-values (n=50, n=25). (V)
6 DISCUSSION

6.1 3D printing and Experimental methods

Currently, clinicians rely on their intuition when making decisions on surgery and evaluating the nasal cavities of patients. Moreover, since nasal cavities are both complex and three-dimensional, clinicians must rely not only on their intuition, but also their experience and subjective assessment of nasal function to make treatment or operative management decisions. However, due to the three-dimensional complexity of the nasal cavities, it is impossible for a surgeon to evaluate the fluid mechanical consequences of their decision making. Such information requires a solution to the Navier-Stokes equations that govern airflow in the nasal cavities. Patient images can be used to create a computational mesh for CFD simulations that can solve these equations. The CFD results can then be used to evaluate the effect of surgical procedures. However, the results of the various CFD models need to be validated against the measurements.

In the present study, numerical comparisons between a mathematical model of nasal airflow (CFD) and the measured flow (PIV) in a realistic nasal cavity acquired from CBCT scans were presented for the first time (II). When we compared CFD with PIV, we found that the results were the most convergent in the wider parts of the nasal cavities. The results between CFD and PIV had a fair agreement, which is in line with the findings of other PIV studies (Cozzi et al., 2017; Zubair et al., 2015). A precise comparison between studies is, however, challenging because previous studies have not reported overall numerical comparisons between various CFD models and PIV in the nasal cavities. In addition, the Reynolds numbers, study setups, and the extent and accuracy of the anatomical structures used in previous studies have varied.

In our study (II), CFD succeeded well in all locations with both laminar and turbulent models. As the differences between the models were small, it is difficult to assess which model obtained the most correct results. In our study, a realistic in vivo flowrate was used in inspiratory airflow. This finding supports the suitability
of the laminar flow approximation in studying natural human breathing in the nasal cavities.

The most reliable PIV measurement results are obtained in the middle of the cavity where velocity gradients are usually the smallest and positioning of the measurements is the least troublesome. Conversely, pressure measurements, which were out of the scope of study II, are easier to perform at the walls. The differences are also clear in model scaling between these two approaches. PIV measurements should be made with a large scaling to increase measurement spatial resolution, whereas the opposite is better for pressure measurement ranges. For pressure measurements, however, 3D printing accuracies limit the reduction of the 3D model scaling. In addition, if 3D models need the verification of the CT scans after the 3D model has been produced, CT or CBCT scan accuracy might also limit the reduction of the 3D model scaling.

The detailed and severely obstructed passages of the nasal cavities are generally harder to measure than averaged, idealised or healthy anatomies of the nasal cavities. The severely obstructed nasal cavities are, however, ideal from a CFD validation standpoint, possessing more details from a clinical perspective. Hence, there exists a trade-off between the two objectives. Based on the findings of the current study (II), wider passages with greater model scaling should be preferred from the study geometry or other similar realistic geometries. One option for the better spatial resolution would be to print only the other side of the nasal cavities in the silicone model.

3D printing in plastic was studied as a convenient alternative to silicone models in the global assessment of flow with active anterior rhinomanometry in addition to linear and volumetric measurements (I). The benefits of plastic are cheaper and faster production. We demonstrated the printing of the nasal cavities and maxillary sinuses in 3D prints from CBCT scans acquired from real patients for the first time (I). Moreover, the quality of the 3D prints was verified by imaging the 3D prints with CBCT and comparing the acquired scans with patient data. No scaling or supporting material was used in the plastic 3D prints. The correspondence between the 3D prints and the original patients in volumetric and linear measurements was high (Table 3). However, many of fine structures in the nasal cavities were troublesome to replicate in printing. The most challenging part of replicating the fine structures were ethmoidal cells in the upper part of the nasal cavities. In the volumetric measurements of the maxillary sinuses and in linear measurements, the 3D prints proved to be slightly smaller than in vivo conditions.
Furthermore, the rhinomanometric resistance measurements of the 3D prints were compared to the clinical circumstances (I). A real person’s breathing was used in vivo as in vitro in active anterior rhinomanometry. A scaling formula from laminar fully developed tube flow was used in our evaluation of the rhinomanometric results which increased the correspondence between the in vivo and in vitro results.

Rhinomanometric results were in good agreement when scaled in vitro results were compared to in vivo conditions (Table 4). Rhinomanometric results were likely somewhat affected by the properties of the rigid plastic material used, which might not have corresponded to the actual mucous membrane (I). The elasticity of the mucous membrane is rarely studied. Bates et al. (2019) studied a patient with dynamic imaging in fast cine MRI images. It was observed that the elasticity of the mucous membrane did not follow only aerodynamic forces. Therefore, more studies are needed to better understand the elasticity of the mucous membrane and its effect on the results.

In addition to the dynamic imaging, segmentation thresholds should be studied in more detail to ensure the correct nasal airway segmentations. This would certainly help to study the discrepancy between the CFD and in vivo active anterior rhinomanometry results. In addition, higher resolution in CT or CBCT imaging could help all rhinological studies.

6.2 Volumetric information and CFD calculations compared with subjective assessment (III-V)

Three-dimensional volumetric information can be studied directly from the patients’ CBCT scans. This enables the study of inferior turbinate surgery results pre- and postoperatively (III). In addition, the same CBCT scans can be used in the CFD calculations to study the physiological variables of flow within the nasal cavities in more detail (IV-V).

6.2.1 Volumetry compared with acoustic rhinometry and subjective assessment (III)

Our results showed that inferior turbinate surgeries lead to statistically significantly increased airway volumes and decreased mucous membrane volumes in the
anterior 5 mm to 20 mm parts of the inferior turbinates postoperatively (III). Furthermore, correlations were found between the air volumes in the anterior part of the inferior turbinates and both acoustic rhinometry V2-5 and VAS scores when all pre- and postoperative images were pooled. Similarly, both subjective assessment methods (VAS and GHSI) had a correlation with the anterior turbinate volume measurements when all images were pooled. Our findings are in line with the observations of previous studies, where the subjective measurement methods did not produce strong correlating results with objective clinical assessment methods (André et al., 2009). However, our findings should encourage further studies with slightly more excessive surgical procedures, since the subjective scores improved with larger nasal airways.

6.2.2 CFD calculations compared with subjective assessment (IV-V)

This dissertation presents the CFD results and air volumes within those calculations, subjective VAS and GHSI values and corresponding acoustic rhinometry V2-5 results from inferior turbinate surgeries both preoperatively- and at twelve months postoperatively for what was to our knowledge the largest cohort of patients to date (V).

The aim of inferior turbinate surgery is to reduce turbinate volume and increase airway volume in the operated parts. The CFD results indicate statistically significant decreases in total wall shear forces in the anterior parts of the inferior turbinates postoperatively (Table 5). Furthermore, statistically significant negative correlations were found between total wall shear forces and volumetrically measured absolute air volumes in the operated parts as well as in their changes between the pre- and postoperative conditions (Table 7-8).

In the previous literature, Kimbell et al. (2013) evaluated patients who had undergone septoplasty and found that average wall shear stress (WSS) increased in the obstructed side of the nose postoperatively. However, that study used a different study setting to the one used in this dissertation. For example, in their study, the average WSS was calculated from the whole obstructed cavity and the patient-specific pressure drop across the nasal cavities was assumed to be equal between the pre- and postoperative conditions. At least without this assumption, the results revealed that bilateral inferior turbinate surgery leads to larger air volumes and reduced total wall shear forces in the operated anterior parts postoperatively (Table 5). Since the surgical operations performed were quite local
(IV-V), it is probable that assuming equal pressure losses along the nasal cavities between pre- and postoperative conditions would have also shown reduced total wall shear forces in the operated anterior parts postoperatively, but not to the same extent as in the present studies (IV-V).

For the subjective assessment of patients, our results reveal there were statistically significant total wall shear force changes in the anterior parts of the inferior turbinates compared with VAS changes (n=25) between the pre- and postoperative conditions. Based on our results, it is unclear whether smaller wall shear force values contribute to better VAS subjective improvement because of smaller pressure drops along the nasal cavity or because of the mechanical subjective sensing of reduced wall shear forces at the surface mucous membrane in the anterior parts of the nasal cavities. As wall shear forces act as a mechanical force on the surface of the mucous membrane, it can also affect the mechanical sensing of the nasal airflow. Our nasal obstruction VAS changes compared with pressure drop results from the ambient to the nasopharynx did not obtain results as significant as the decreased wall shear forces in the anterior parts of the inferior turbinates (Table 9). However, form drag is not considered in the wall shear force results. Furthermore, it is unclear how many short- or long-term external factors are present at the time of CBCT imaging. In future, the sensitivity of wall shear forces and the effects of pressure loss on the VAS assessment could possibly be studied by creating conditions where breathing effort is changed while pressure losses across the nasal cavity remain constant. At the same time, VAS assessments should be collected.

Several virtual studies of bilateral turbinate surgery have shown decreased total heat transfer (Chen et al., 2010; Siu, et al. 2021; Hariri et al., 2015). In virtual studies, artificial bilateral theoretical surgery is often performed, and the effects of the surgery are evaluated computationally. Similarly, for real life patients, our pilot study (IV) reported reduced heat transfer results in the operated parts for inferior turbinate surgery postoperatively. For a larger cohort, the heat transfer in the operated parts did not decrease significantly (V). With a greater number of patients, however, our results could have possibly shown statistical significance in those results. In the present study, it should be noted that Weber-Fechner transformation of the results did not improve heat transfer correlations compared with subjective assessments (Table 7-8). This transformation has similarities to SAHF50 presented in other studies (Table 2). In addition, heat transfer correlation compared with V2-5 and air volumes changed into a positive direction after Weber-Fechner
transformation observed air volume contribution to heat transfer in a different manner compared to the results without this transformation (Table 7-8).

CFD studies with pre- and postoperative images and subjective assessments are still rare. Previously, the results of other pre- and postoperative CFD studies have been reported after concomitant septorhinoplasty or septoplasty and turbinate surgery in patients with turbinate hypertrophy and septum deviation (Table 2). In those studies, the CFD results were usually analysed for the whole nasal cavities separately for the most obstructed side and for the more unobstructed side. These studies have shown increased heat fluxes or total heat transfer from the most obstructed side of the nose postoperatively (Sullivan et al., 2014; Gaberino et al., 2017, Kimbell et al., 2013). Furthermore, Na et al. studied bilateral septoturbinoplasty (n=8) and found a correlation between the NOSE scores and an increase in surface heat flux from the most obstructed side. In those studies, pressure losses were assumed to be equal between pre- and postoperative conditions. In this dissertation (IV-V), however, volume flowrates were assumed to be equal between pre- and postoperative conditions. Between these two assumptions exists the assumption of breathing power being equal between pre- and postoperative conditions. Breathing power is proportional to a product of pressure drop and volume flowrate. To the best of our knowledge, no pre- and postoperative studies have this assumption. However, Segalerba et al. (2023) introduced the concept for the nasal airflow by conducting virtual surgery comparisons between the three assumptions and the results showed differences.

In most other studies, NOSE scores obtained greater or similar CFD correlations than nasal obstruction VAS scores compared with CFD variables (Sullivan et al., 2014; Gaberino et al., 2017, Kimbell et al., 2013; Casey et al., 2017). In this dissertation, general QOL results were collected from the GHSI questionnaire instead of the NOSE surveys. It remains unclear, however, why our GHSI questionnaire did not have comparable correlations such as VAS results compared with objective CFD measures, as was observed in many other studies. It might be that the patients’ septoplasty operations contributed to patient QOL more than the similar bilateral surgical operations performed in our patient cohort. It should be noted that our nasal resistance ratios between pre- and postoperative results are probably smaller than in other studies (Gaberino et al., 2017, Kimbell et al., 2013; Na et al., 2022) which often involved septoplasty. Our pressure loss results (Table 6) might indicate this, although direct comparisons are challenging.

Our results assume that inspiratory flow rates are independent from surgery volumetric changes and that patients breathe as much pre- and postoperatively as
corresponding healthy subjects. Interestingly, this assumption is also often made in virtual or theoretical studies. It can be expected that this assumption holds true for a large majority of patients. However, many pre- and postoperative studies have assumed that postoperative pressure loss was equal to the preoperative pressure loss which resulted in reduced flow rates preoperatively and assumed that a part of breathing goes through the mouth preoperatively (Table 2) (Sullivan et al., 2014; Gaberino et al., 2017, Kimbell et al., 2013; Na et al., 2022). The problem with this assumption is that surgical operations affect the preoperative volume flowrates. In future, more detailed patient information on possible mouth breathing should be collected. The difficulty is that patients should be ideally followed in daily life for these purposes. Although NOSE scores have a question that considers mouth breathing, the quality of life GHSI questionnaire used in this dissertation does not. To the best of our knowledge, this somewhat subjective NOSE questionnaire information has not been utilised in other CFD studies. It is probable that a patient specific pressure threshold across the nasal cavities exists, where partial mouth breathing is first observed. This pressure threshold is probably dependent on whole breathing geometry from the nostrils to the lungs and the patient’s capability to perform breathing work. It would also be beneficial to model the lower parts of the airways for these purposes. Perhaps artificially created breathing conditions could help the study of patient specific pressure thresholds for nasal breathing in future setups.

Calculated heat transfer is subject to assumptions about nasal mucosal temperatures. We approached these calculations by not assuming a constant mucosal temperature along the nasal cavity, but instead by varying nasal mucosal temperatures as a function of heat transfer itself. This approach was a numerical fit to the experimental mucosal temperatures along the nasal cavity (Lindemann et al., 2002). Furthermore, our approach assumes that mucosal temperature is 37 °C while local heat transfer is not present. Unfortunately, temperature data are very scarce along the nasal cavity and few studies have been made. Moreover, it could be that our assumption is not completely true either and may have resulted in too much variation in the nasal mucosal temperatures along the nasal cavities. Our temperature boundary condition had a numerical value equal to the effective mucous membrane resistance used in a few studies (Senanayake et al. (2021); Tjahjono et al., 2022). Many other studies (Table 2) have mostly used constant mucous membrane surface temperatures, although in recent years theoretical studies with varying mucosal temperatures have been increasingly developed (Senanayake et al., 2021; Byun et al., 2019; Kim et al., 2017; Inthavong et al., 2022;
Na et al., 2020; Chung et al., 2021) A similar kind of assumption of mucosal temperatures as a function of heat transfer have been made in this dissertation (IV-V). In addition, it should be noted that surgical procedures lead to decreased mucous membrane volumes. These coupling effects are yet to be accounted for in heat transfer calculation procedures, where many studies have used constant mucous membrane thickness in the whole nasal cavity in all conditions. Neither the two studies in this dissertation (IV-V) nor other studies in the literature have taken these effects into account.

Most studies have assumed the monotonicity of the CFD results compared with subjective assessments when analysing the results with Pearson or Spearman correlations. Our results also used this assumption and the monotonicity assumption was true in all correlations. However, it is probable that too excessive surgical operations would lead to empty nose syndrome and other negative effects, which would violate the use of Pearson or Spearman correlation. Apparently, these kinds of manoeuvrers are not present in the current literature with pre- and postoperative setup studies. Therefore, in future, slightly more excessive surgeries should be conducted for research purposes.

### 6.3 Strengths and limitations

To the best of knowledge, our studies had the most clinically homogenous patient cohort in CFD studies to date (IV-V). As our operations were similar for each patient, it is difficult to say to what extent different mucous membrane properties affect subjective assessment improvements. In future, surgical procedures should also be documented in detail to differentiate similar postoperative CFD changes from different postoperative mucous growth between patients to reveal mucous membrane properties and their relation to VAS improvements. Furthermore, our surgical procedure and patients’ subjective assessment of the severity of the nasal obstruction differ in several important ways from previous study settings. Our surgical procedure was concentrated on the anterior parts of the inferior turbinates with similar operations performed on all patients. Therefore, the operated parts were smaller, and the surgical procedures performed were more similar and local than septoplasty patients have previously undergone. In our results, the correlations between VAS changes and heat transfer changes in the operated parts were not statistically significant. However, changes in wall shear force value in the operated parts had significant correlations compared with the patients’ subjective
assessment changes. Based on the findings of our studies, local wall shear force changes could be at least as informative as heat transfer in the patients’ subjective assessment of the severity of nasal obstruction. Future studies should concentrate on studying and reporting these results in more detail.

All results, heat transfer and pressure losses are affected by external and internal factors, such as nasal cycle. Nasal cycle modelling was not used in this dissertation. Some studies have used the nasal cycle modelling procedure or its absence as a patient selection method. However, nasal cycle modelling is controversial and not without problems if surgical procedures are involved. It is sometimes difficult to separate the effects of the nasal cycle and other internal and external factors from surgical results. Therefore, many studies have used ad hoc methods of observing nasal cycle information as an inclusion or exclusion criteria for pre- and postoperative setups. Alternatively, nasal cycle corrections can be done computationally (Patel et al., 2015; Gaberino et al., 2017). This computational approach removes the effects of nasal cycling from patient images but not from instantaneous subjective assessments. In future, one option could be to combine operated nasal regions separately for pre- and postoperative external nasal geometry to gain more information about the effects of the nasal cycle on CFD results for setups where operations are local. Alternatively, nasal cycling could be modelled to probabilities by combining CT imaging and rhinomanometric data. The problem is that intra-subject data are still very limited in clinical practice and rhinomanometric data obtain less detailed information and have more measurement uncertainty than CT imaging information.

The latent heat present in moisture transfer has been found to be one order of magnitude higher than sensible heat transfer (Inthavong et al., 2022, Na et al., 2022). Sensible heat transfer was calculated in two studies of this dissertation (IV-V). In future studies, moisture transfer compared with subjective assessments should be studied in more detail. The difficulty is that patient specific moisture boundary conditions should be known as well. Moisture transfer modelling has recently been improved (Inthavong et al., 2022).

In some of the other CFD studies (Casey et al., 2017; Sullivan et al., 2014; Gaberino et al., 2017), instantaneous patient VAS results were investigated unilaterally while the other side of the nose was blocked. This is, however, different from CFD calculations, where the nasal airflow is bilateral. It is challenging to evaluate how well the patients’ subjective assessment changes from natural breathing conditions as modelled in CFD calculations to an instantaneous unilateral subjective assessment of the severity of nasal obstruction with covered
nostril conditions. In our studies (III-V), we did not use instantaneous nasal obstruction VAS assessment separately for both sides of the nasal cavities. Instead, the patients’ bilateral nasal congestion VAS assessment was collected from the previous seven days. For all QOL questionnaires, similar or longer time periods for the assessment are used. The choice of different VAS assessment is challenging and depends greatly on the patient cohort studied and the timing of the imaging procedure.

6.4 Future clinical applications of CFD

In this dissertation, it has been shown that CFD models can be used for studying nasal airflow and the effect of inferior turbinate surgeries pre- and postoperatively. In future, CFD calculations need to be automated to better help the clinician in decision making. Perhaps artificial intelligence or adjoint optimisation methods could help to develop these goals. Also, in future, CT imaging information could be enough to perform an automated analysis of the patency of nasal cavities. To date, these kinds of methods are rare or non-existent in nasal airflow studies and clinical practice. However, certain automations of the CFD procedure have been made with Lattice Boltzmann methods (Rüttgers et al., 2022; Berger et al., 2021b).

In addition, larger cohorts with various heterogenous operations need to be studied with subjective assessments to better understand the physiological variables which affect the subjective severity of nasal obstruction VAS and quality of life scores. In addition, it would be convenient if the boundary conditions needed for the CFD calculations could be collected in clinical practice more automatically and patient specifically, as this could enhance the correspondence between CFD calculations and patient specific conditions. While being useful, the current quality of life questionnaires used for clinical evaluation do not account for CFD calculations boundary conditions. Regardless of the VAS assessment used in current academic nasal congestion studies, all efforts should be given to enhancing the patients’ longer term VAS assessment in future clinical CFD applications.

Currently, the information obtained from CT or CBCT scans is not used to its full extent in clinical practice. In most cases, CT or CBCT scans are used in the examination of patients with chronic rhinosinusitis. The information provided by scans can, however, be used in CFD calculations to comprehensively study nasal airflow and nasal congestion in the nasal cavities. The results of the present studies demonstrate that CFD can assess differences in airflow quantities between pre- and
postoperative conditions. These methods provide future possibilities for assessing nasal congestion and its effect on patients.
7 CONCLUSIONS

1. 3D printing in PLA filament was able to replicate the nasal cavities with sufficient accuracy modelling for clinical use. On average, in vivo and in vitro active anterior rhinomanometry measurements were in good agreement with each other.

2. PIV measurements serves as a tool for CFD model validations well for nasal airflow in wider parts of the nasal cavities and larger scaling would benefit measurement accuracy in all areas of the nasal cavities.

3. Objective measures from CBCT scans had statistically significant correlation with subjective assessments. Patient CBCT imaging data are accurate enough and should be analysed in three dimensions for clinical evaluation in addition to cross-sectional 3D analysis.

4. CFD simulations revealed airflow changes in the nasal cavity after surgical intervention. Airflow wall shear forces decreased postoperatively as flow gradient decreased between nasal mucosa and airflow. Subjective nasal patency changes between pre- and postoperative conditions correlated significantly to the wall shear force changes in the operated area in inferior turbinate surgery.
8 REFERENCES


Three-Dimensional Printing of the Nasal Cavities for Clinical Experiments

Valtonen O, Ormiskangas J, Kivekäs I, Rantanen V, Dean M, Poe D, Järnstedt J, Lekkala J, Saarenrinne P, Rautiainen M

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Three-Dimensional Printing of the Nasal Cavities for Clinical Experiments

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3D printing has produced many beneficial applications for surgery. The technique’s applicability in replicating nasal cavity anatomy for clinical use has not been studied. Our aim was to determine whether 3D printing could realistically replicate the nasal cavities and the airflow passing through them from a clinical point of view. We included Cone Beam Computed Tomography (CBCT) scans of five patients with symptoms of chronic nasal congestion. These CBCT scans were used to print plastic 3D prints of the nasal cavities, which were also CBCT scanned and the measurements were compared. The results in vivo were higher than the results in vitro in maxillary sinus volumes with a ratio of 1.05 ± 0.01 (mean ± SD) and in the nasal cavities with a ratio of 1.20 ± 0.1 (mean ± SD). Linear measurements in vitro were very close to those in vivo. Rhinomanometric results showed some differences, but rhinomanometric graphs in vitro were close to the graphs in vivo. 3D printing proved to be a suitable and fast method for replicating nasal cavity structures and for the experimental testing of nasal function. It can be used as a complementary examination tool for rhinomanometry.

Recently, 3D modelling and printing technology have been used in a variety of medical applications, such as surgical planning, design of implants and tissue for individual patients, research and as an educational and training tool1. 3D modelling and printing technology have also been used for the planning of implants and operations for craniofacial and skull base pathologies2. In addition, the technology has been used in the planning of head and neck tumour surgery3. The technology also offers vast possibilities in the field of reconstructive surgery4.

To date, however, not all the possibilities offered by 3D printing technology have been utilised in clinical practice. For example, due to the complicated anatomy of the nose, 3D printing technology has not yet been used for modelling of the anatomy of the nasal cavities for clinical purposes or as a tool for the planning of nasal surgical procedures.

Previously, individual models of the anatomy of the nose and nasal cavities were 3D modelled in silicone5–8. The production of these models was, however, slow and labourious. These models were used to study airflow in the nasal cavities using liquid and small particles as substances, but the results were not compared with measurements from actual patients. The methods used were particle image velocimetry (PIV) and computational fluid dynamics (CFD), both of which are labourious and time-consuming methods.

In the present study, our main objective was to assess whether 3D printing could be used to realistically replicate the nasal cavities and the airflow passing through them from a clinical viewpoint. We investigate the applicability of plastic 3D prints of the nasal cavities and paranasal sinuses printed from cone beam computed tomography (CBCT) acquired images. A secondary objective was to determine how well the plastic 3D prints corresponded to the nasal function in vivo.
Materials and Methods

CBCT scans of five adult patients with symptoms of chronic nasal congestion were included in this study. In total, ten individual nasal cavities and maxillary sinuses were studied. Exclusion criteria were chronic sinusitis, nasal cavity polypos and tumours. CBCT was used for patient imaging and data acquisition due to its generalised use for this patient group in our hospital. CBCT exposes patients to a relatively low dose of radiation, less than conventional high resolution CT (Hounsfield units (HU)). For CBCT imaging, we used the Scannora™ 3Dx (Soredex, Inc., Tuusula, Finland). The following imaging parameters were used: 0.2 mm CT slice thickness, voxel size 0.2 mm, 90 kVp, 8 mA and 4 s radiation time.

The plastic 3D prints were printed from CBCT scans acquired from the patients. After imaging, the CBCT data were saved in Digital Imaging and Communications in Medicine (DICOM) format. Matlab® software (MathWorks Inc., Natick, Massachusetts, United States) was then used to process the DICOM images. The CBCT scans were then combined by stacking the 2D image slices, resulting in a 3D model with a voxel size of 0.2 mm in x, y and z directions. Each image slice in the x-y plane was pre-processed by removing noise with a square-shaped average filter and emphasizing the edges in the image using unsharp masking. Then, the tissue types were classified based on voxel light density values. The areas with the density values greater than the values of the areas of the pneumatised volumes were considered solid, and thus the grayscale 3D model was converted to a binary model. The model was corrected by removing small disconnected regions by performing a morphological opening of the 2D image slices along each axis. Finally, the data were saved in Standard Tessellation Language (STL) format for the 3D printing. Before printing, the STL models were processed with Blender software (The Blender Foundation) by using the Remesh operation to fix any possible errors in the models and to make them compatible with the Slic3r software (open source 3D slicing engine) that was used to generate the toolpaths for the printer.

The plastic 3D prints were produced on a Lulzbot® Taz 4 3D printer (Aleph Objects, Inc., Loveland, Colorado, United States) using the Fused Deposition Modelling (FDM) printing technique with a nozzle size of 0.4 mm and a layer thickness of 0.25 mm. In the FDM printing technique, the raw material is deposited through a print head. The extruded string of fused thermoplastic material is immediately bound to the layer below. Polylactic acid (PLA), a commonly used corn-based thermoplastic material for 3D printing, was used as the raw material.

The plastic 3D prints were printed from the level of the nasopharynx to the level of the frontal sinus in 1:1 size. Since it would have been challenging to remove supporting structures afterwards, no supporting structures were generated for the 3D prints. The printing of one plastic 3D print took approximately 48 hours. No additional clean-up of the printed objects was required. However, some printing artefacts were left in the cavities after printing due to the lack of supporting structures for the overhanging parts. When all five 3D prints had been printed, CBCT images were taken of each print for further analysis and to confirm that the prints corresponded with the data of the real patients.

The volumetric measurements of the pneumatised volumes in the patients’ nasal cavities and maxillary sinuses were measured from the patient’s CBCT scans by using pixel light density values from –1000 to –430 Hounsfield units (HU). The same values were also used for measuring pneumatised volumes in CBCT scans in our previous study. The volumetric measurements were made using OnDemand3D™ (version 1.0, CyberMed, Inc., Yuseong-gu, Daejeon, South Korea). For volumetric measurements of the 3D prints, the equivalent pixel light density values for the CBCT scans were defined with the measuring software’s scaling function to be from –1000 to –800 HU due to the printing material used. Similar nasal cavity and maxillary sinus volumetric measurements were evaluated from all CBCT scans. The volumetric software (OnDemand3D™) used in our study often included excess structures in the areas of the volumetric measurements despite the defined values. However, these structures were manually excluded.

Linear measurements in the nasal cavities were made using the same software in all three dimensions in the following way: septum length from the tip of the nose to the closest endpoint of the nasal septum, nasal cavity height at the same endpoint of the nasal septum and the width of the nasal cavity at the same location (Fig. 1). These benchmarks were chosen due to the lower risk of artefacts.

Rhinomanometric resistance measurements of the patients and the 3D prints were also compared. The measurements were done by using anterior rhinomanometry with an NR6 Rhinomanometer (GM Instruments Ltd, Kilwinning, Scotland, United Kingdom) and Nasal Acoustic Rhinomanometer Information System (NARIS) version 3.2 software (GM Instruments Ltd, Kilwinning, Scotland, United Kingdom). The results were measured from the airflow rates by using the Broms method. Rhinomanometry from the 3D prints was done by using the same instrument as used with real patients. In rhinomanometry, the airflow was produced by one of the investigators breathing through a plastic tube connected to the nasopharynx of the 3D prints.

In rhinomanometry, one of the patients and the corresponding 3D print were excluded from this analysis because the patient’s rhinomanometry failed technically. This was noticed after the patient had undergone a nasal operation that resulted in the circumstances in the nose being altered from the original situation, and therefore another rhinomanometry could not be done reliably. As a result, a total of eight individual nasal cavities and maxillary sinuses were studied with rhinomanometry.

Due to the printing induced volume and linear measurement differences observed between the patient and the 3D print measurements, we used a scaling formula to make the rhinomanometric results in vitro comparable with the results in vivo. Furthermore, we assumed the airflow in the nose being laminar rather than turbulent in the scaling due to the mild flow rates stemmed from the use of Broms method. Thus, the scaling was based on an analogy from laminar tube flow Hagen-Poiseuille equation by taking into account nasal cavity volumes and septum lengths. The scaling for the unilateral rhinomanometric results in vitro was calculated by using the following formula derived from Hagen-Poiseuille equation: results in vitro multiplied by nasal septum length ratio (in vivo/in vitro) to the power of three divided by nasal cavity volume ratio (in vivo/in vitro) squared.

In addition, due to the relatively small number of cases and the deviation of the rhinomanometric results, the use of geometric mean instead of arithmetic mean was found to be more illustrative in presenting the
The geometric standard deviation (GSD) was calculated using the following formula:

\[ \text{GSD}(X) = e^{\text{SD} \ln(X)} \]

where \( e \) is Euler number, SD is arithmetic standard deviation, \( \ln \) is natural logarithm and \( X \) is measurements.

Institutional review board approval for the study was obtained from Tampere University Hospital, Tampere, Finland. This study was carried out in accordance with the Declaration of Helsinki. Prior to collection of patient data, informed consent was obtained from all participants. All patient data were acquired from the medical records database of Tampere University Hospital.

**Results**

We were able to perform reliable measurements both with the patient and 3D print CBCT scans (Table 1). In the volumes of the maxillary sinuses, the results in vivo were higher with a ratio of 1.05 ± 0.01 (mean ± SD) compared with the volumetric results in vitro (Table 2). In the nasal cavities, the volumetric measurements were higher in vivo with a ratio of 1.20 ± 0.1 (mean ± SD) when compared with the results in vitro. In every linear measurement, the results were higher in the measurements in vivo: 1.03 ± 0.02 (mean ± SD) in nasal septum length, 1.04 ± 0.03 (mean ± SD) in the height of the nasal cavity and 1.06 ± 0.1 (mean ± SD) in the width of the nasal cavity.

In rhinomanometric results, the resistance in vivo was less in inspiration with a geometric mean ratio of 0.77 and in expiration with a ratio of 0.71 (Table 3). Standard deviation factors were 2.78 and 2.32, respectively. When the results in vitro were scaled based on nasal cavity volume and septum length differences, the similar ratios were 1.03 and 0.95 with standard deviation factors of 2.86 and 2.39, respectively. The total rhinomanometric resistance results were analogous to the unilateral measurement results. The graphs in vitro generated by the rhinomanometric software were close to the conditions in vivo (Fig. 2). The rhinomanometric graphs are provided more comprehensively in the Supplementary Information (Suppl. Inf.).

**Discussion**

In the present study, we demonstrate the printing of the nasal cavities and maxillary sinuses in 3D prints from CBCT scans acquired from real patients for the first time. Moreover, the quality of the 3D prints were, for the first time, verified by imaging the 3D prints with CBCT and comparing the acquired scans with the patient data. The correspondence between the 3D prints and the original patients in the volumetric and linear measurements was high. Furthermore, we compared the rhinomanometric resistance measurements of the 3D prints to the clinical circumstances. For the first time, in order to better model clinical circumstances, we used a real person's breathing...
### Table 1. Measurements from every patient and corresponding 3D prints. Rhinomanometric results from patient 5 and corresponding 3D print were excluded due to a technical fail.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Septum length (mm)</th>
<th>Septum height (mm)</th>
<th>Nasal cavity width (mm)</th>
<th>Maxillary sinus volume (cm³)</th>
<th>Nasal cavity volume (cm³)</th>
<th>Rhinomanometry, inspiration (Pa/[cm³/s])</th>
<th>Rhinomanometry, expiration (Pa/[cm³/s])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>81.0</td>
<td>43.2</td>
<td>17.3</td>
<td>18.0</td>
<td>10.4</td>
<td>0.112</td>
<td>0.376</td>
</tr>
<tr>
<td>2</td>
<td>84.8</td>
<td>48.9</td>
<td>10.6</td>
<td>16.3</td>
<td>15.6</td>
<td>0.212</td>
<td>0.133</td>
</tr>
<tr>
<td>3</td>
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<td>45.6</td>
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<td>20.7</td>
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<td>4</td>
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<tr>
<td>5</td>
<td>77.0</td>
<td>42.9</td>
<td>23.3</td>
<td>24.3</td>
<td>21.4</td>
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</tbody>
</table>

### Table 2. Mean volumetric (cm³) and linear (mm) results (mean ± SD). Five patients (10 maxillary sinuses and nasal cavities, 5 nasal septums) and the corresponding 3D prints are included. In comparison, the mean ratio of the measurements is calculated by comparing the measurements in vivo and in vitro. Standard deviation of the comparison is shown as percentage points.

<table>
<thead>
<tr>
<th></th>
<th>Maxillary sinuses (cm³)</th>
<th>Nasal cavities (cm³)</th>
<th>Nasal septum length (mm)</th>
<th>Nasal cavity height (mm)</th>
<th>Nasal cavity width (mm)</th>
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<tbody>
<tr>
<td>In vivo</td>
<td>17.9 ± 4.0</td>
<td>15.9 ± 3.8</td>
<td>82.6 ± 5.2</td>
<td>45.1 ± 2.4</td>
<td>18.7 ± 5.2</td>
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<tr>
<td>In vitro</td>
<td>17.1 ± 3.9</td>
<td>13.4 ± 4.1</td>
<td>80.5 ± 5.3</td>
<td>43.5 ± 2.3</td>
<td>17.8 ± 5.5</td>
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<tr>
<td>Comparison</td>
<td>1.05 ± 0.01</td>
<td>1.20 ± 0.1</td>
<td>1.03 ± 0.02</td>
<td>1.04 ± 0.03</td>
<td>1.06 ± 0.1</td>
</tr>
</tbody>
</table>

### Table 3. Geometric mean rhinomanometric resistance measurements (Pa/[cm³/s]). Geometric standard deviation factors are presented in brackets. Inspiratory and expiratory results include eight different nasal cavities from four patients and corresponding 3D prints. The total results from the four patients and 3D prints take both left and right nasal cavities into account. In comparison, the geometric mean ratio of the measurements is calculated by comparing the measurements in vivo and in vitro. The scaled results in vitro and corresponding comparison are also presented. GM = Geometric Mean, GSD = Geometric standard deviation factor.

<table>
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<th>Inspiration (GSD)</th>
<th>Expiration (GSD)</th>
<th>Total inspiration (GSD)</th>
<th>Total expiration (GSD)</th>
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<td>In vivo</td>
<td>0.58 (2.34)</td>
<td>0.61 (2.52)</td>
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<td>In vitro</td>
<td>0.76 (3.19)</td>
<td>0.87 (2.89)</td>
<td>0.28 (2.96)</td>
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<td>Comparison</td>
<td>0.77 (2.78)</td>
<td>0.71 (2.32)</td>
<td>0.81 (2.49)</td>
<td>0.71 (1.81)</td>
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<td>In vitro (scaled)</td>
<td>0.57 (3.13)</td>
<td>0.64 (2.87)</td>
<td>0.22 (3.11)</td>
<td>0.26 (2.84)</td>
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<tr>
<td>Comparison with in vivo and scaled results in vitro</td>
<td>1.03 (2.86)</td>
<td>0.95 (2.39)</td>
<td>1.04 (2.66)</td>
<td>0.91 (1.97)</td>
</tr>
</tbody>
</table>

to provide the airflow of the 3D prints. According to our findings, the accuracy of the 3D prints of the nasal cavities both structurally and functionally are so close to the original circumstances that the 3D prints can be used for the modelling of the nasal cavities in vitro.

In the volumetric measurements of the maxillary sinuses and linear measurements, the 3D prints proved to be slightly smaller than the actual patients, although, the differences were small (Table 2). When it comes to measuring the relatively well-bordered anatomical structures using the volumetric method in 3D prints, the results are very close to the conditions in vivo. The maxillary sinuses can be accurately isolated for measuring, thus, the volumetric measurements in maxillary sinuses are reliable and can be used in size comparison. In the nasal cavities, artefacts produced in printing the delicate structures of the nasal cavities were the reason for high result in this comparison. Linear measurements also proved to be very close to the original measurements due to the absence
of major artefacts in the measuring points of the 3D prints. Moreover, during printing, the size of the 3D prints can be scaled according to the desired size, which gives added versatility to this printing method.

Caution is always required in replicating small and detailed structures as artefacts may be introduced into the 3D print, but despite this the printed result was satisfactory. In our study, the most challenging part of replicating the nasal cavities was to replicate the upper part of the nasal cavity together with the ethmoidal cells. These anatomical structures were vulnerable to any kind of image artefact in the original CBCT scans. In addition, the lack of supporting structures during the printing phase also caused our 3D prints to be exposed to printing artefacts, for example, print surface roughness and narrower structures. Furthermore, we noticed that printing these delicate structures starting from the bottom of the nasal cavity meant that some of the structures were left without any support, and thus, there was the risk of collapse. In most of the models, the upper nasal cavities were narrowed and the inferior nasal conchae had bent under weight. This caused the actual pneumatised area to diminish, which can also be seen in our nasal cavity volume results. These printing technique induced artefacts could most likely be avoided, for example, by beginning printing from above and, if it is practically possible, using soluble supporting structures during the printing process.

Similar observations regarding artefacts with fine anatomical structures were also made in a study where producing 3D prints caused an overall dimensional error of 2.67% for a 3D model of a dry skull. However, the thin bones, small foramina and acute bone projections were not printed as accurately as the rest of the structures.

In the modelling of sinonasal structures, 3D printing would be a reliable tool for research purposes and also an option for PIV experiments and CFD modelling. The 3D printing method is faster, easier and more affordable than PIV and CFD with silicone models, which can take from days to weeks to perform. However, PIV experiments do have a future in the exact assessment of airflow in the nasal cavities, which is not possible with the presented method. In our study, the plastic 3D prints were produced in two days. The printing time can be reduced by changing the scale of the 3D prints. The nozzle of the printer and layer thickness can also be changed, thereby affecting the printing time. However, these changes will also have an effect on the surface precision of the 3D prints. In addition, the 3D printing process can be automated, and the procedure can be performed around the clock.

Figure 2. Corresponding results in vivo and in vitro. Above: Axial CBCT image (A) from a patient and rhinomanometry (B) from the same patient. Below: Corresponding CBCT image (C) and rhinomanometry (D) from the 3D print.
We were able to perform rhinomanometric measurements using the 3D prints. The resistance to airflow proved to be higher in vitro compared to the results in vivo (Table 3). When the results in vitro were scaled based on nasal cavity volumes for a more realistic comparison, the results in vivo and in vitro were closer to each other. This indicates that rhinomanometric results from various sizes in vitro could be scaled with reasonable accuracy to make cases comparable to rhinomanometry in vivo.

Rhinomanometric results in our study were likely affected by the properties of the rigid plastic material used as it, in terms of its qualities, was not directly proportional to the actual mucus membrane. In future studies acrylonitrile butadiene styrene (ABS) could be considered an alternative rigid material to PLA. Another option, for example, could be thermoplastic polyurethane (TPU) which is more elastic than PLA. Furthermore, many of the delicate structures in the nasal cavities were troublesome to replicate in printing, with the result of narrowing of some structures that could affect the results. The 3D prints, although printed in 1:1 size, proved to be slightly smaller than the actual patients, which necessitated our use of a scaling formula in our evaluation of the rhinomanometric results.

Our rhinomanometric measurements were conducted with normal breathing. However, temporal information of breathing flow rates was not given by our rhinomanometry device. To be precise, breathing flow rates should be temporally identical between in vivo and in vitro to be completely certain of a correct comparison. Therefore, the time dependency of the rhinomanometric results should be investigated in future. In a similar way, completely stationary flow resistances should be compared to the present rhinomanometric results. Such studies could reveal important information of how unsteady flow may affect rhinomanometric results. In addition, it has been previously reported that rhinomanometric results in vivo could be considerably higher than those obtained by time independent CFD. The time dependence of the rhinomanometric results could be an important factor in explaining such differences.

Our 3D modelling method makes all additionally mentioned flow resistance measurements possible. We could expect temporally identical rhinomanometric measurements to reduce the standard deviations in mean ratios between in vivo and in vitro compared with the present results. Already in the current study, comparison ratios with nasal cavity scaling produced results with reasonable agreement.

Conclusions
3D printing technology proved to be a suitable and fast method for replicating nasal cavity structures and for the experimental testing of nasal function. The technology enables the detailed study of rhinomanometric measurements, and thus can be used as a complementary examination tool for rhinomanometry for clinical and research purposes. More study to optimise the printing techniques, print materials and modelling processes is warranted to refine this promising model.

Data availability
All data are available on request.

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References

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**Author contributions**
All authors took part in designing the study. O.V., J.O., V.R., I.K. and J.J. performed the experiments and measurements. O.V. and J.O. processed all the data. O.V. produced all the tables and figures. O.V. and J.O. wrote the manuscript and I.K., P.S. and M.R. provided comments. All authors took part in finalising the manuscript and approved it.

**Competing interests**
The authors declare no competing interests.

**Additional information**
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Assessment of PIV performance in validating CFD models from nasal cavity CBCT scans

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Assessment of PIV performance in validating CFD models from nasal cavity CBCT scans

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ARTICLE INFO

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PIV
nasal airflow
CBCT
3D silicone modelling

ABSTRACT

Objective: The aim of our study was to investigate how well Particle Image Velocimetry (PIV) measurements could serve Computational Fluid Dynamics (CFD) model validation for nasal airflow.

Material and methods: For the PIV measurements, a silicone model of the nose based on cone beam computed tomography (CBCT) scans of a patient was made. Corresponding CFD calculations were conducted with laminar and two turbulent models (k-ω and k-ω SST).

Results: CFD and PIV results corresponded well in our study. Especially, the correspondence of CFD calculations between the laminar and turbulent models was found to be even stronger. When comparing CFD with PIV, we found that the results were most convergent in the wider parts of the nasal cavities.

Conclusion: PIV measurements in realistically modelled nasal cavities succeed acceptably and CFD calculations produce corresponding results with PIV measurements. Greater model scaling is, however, necessary for better validations with PIV and comparisons of competing CFD models.

1. Introduction

Currently, clinicians have rudimentary analysis tools at their disposal with which to assess the nasal cavities. The most commonly used rhinometric measurements for the assessment of the nasal cavities are rhinomanometry and acoustic rhinometry. Vogt et al. have previously published an excellent review on the subject of rhinomanometry (Vogt, Jalowayski et al., 2010). Unfortunately, a patient’s subjective assessment does not always correlate with objective clinical measurement methods (André et al., 2009; Nip et al., 2018).

Clinicians, therefore, have to rely on their experience, intuition and subjective assessment of nasal function upon which to base their treatment or operative management. Due to the three dimensional complexity of the nasal cavities, it is impossible for the surgeon to evaluate the fluid mechanical consequences of surgical manoeuvres. Such information requires a solution to the Navier-Stokes equations that govern airflow in the nasal cavities. Fortunately, computed tomography (CT) and cone-beam computed tomography (CBCT) scans of the patient can be used to create a computational mesh for Computational Fluid Dynamics (CFD) simulations that can solve these equations.

CFD modelling of the nasal cavities is not, however, straightforward. The fundamental question in nasal airflow is whether it remains laminar or is partly turbulent. In addition, airflow also varies as a function of time and location in the nasal cavities. Due to these and other challenges, researchers have conducted CFD studies using various approaches. Quadrio et al. (2014) have carried out an excellent review of CFD studies. Similar reviews have also been published in which the challenges of the clinical use of CFD have been discussed (Zubair et al., 2012; Kim et al., 2013).

Turbulence modelling is usually based on the widely used Reynolds-
averaged Navier-Stokes (RANS) models, which rely on Reynolds averaging of turbulent fluctuations. The most common approach to the problem is to use two-equation RANS models that introduce the Boussinesq linear eddy viscosity assumption, where turbulent viscosity is assumed to be isotropic and is a property of the flow. These two-equation models, such as k−ε, k−ω and k−ω SST, are reasonably good for most cases. Further from the scope of RANS turbulence modelling, Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS) are more detailed but computationally often too expensive, which make them inconvenient for practical use.

The various CFD models need validation of the results. These results are often very case specific because no universally optimal RANS model has been found. Particle Image velocimetry (PIV)-based measurements with transparent silicone models can be applied for these CFD validations. Nasal cavity airflow in vitro has been studied with Stereoscopic Particle Image Velocimetry (SPIV) (Spence et al., 2011; Spence et al., 2012). There have also been studies where PIV and CFD have been used for the study of nasal cavity airflow (Doorly et al., 2008; Chung and Kim, 2008; Na et al., 2012; Zubair et al., 2015; Lintermann and Schröder, 2017). Cozzi et al. (2017) conducted SPIV and LES calculations, where the maxillary sinuses were also included in the silicone model.

The clinical treatment of the nose would benefit from a planning tool that uses CT imaging, analyses the patient’s problems and provides suggestions for the diagnosis and proper surgical or medical treatment. Such a diagnostics and surgical planning tool could be based on results obtained from CFD. In order to select the optimal CFD model, we would need a comparison to PIV measurements. Unfortunately, previous PIV studies have lacked overall comparisons between PIV and various CFD models. Therefore, this study aims to investigate how well PIV measurements can serve CFD model validation in studies of the nose. For this purpose, laminar and two turbulent CFD models (k−ω and k−ω SST) are compared with PIV measurements in a silicone model of the nasal cavities.

2. Material and Methods

Institutional review board approval for the study was obtained from Tampere University Hospital, Tampere, Finland. All patient data were acquired from the medical records database of Tampere University Hospital.

A nasal airflow corresponding to the constant inspiratory flow rate of calm breathing of 10 l/min in vivo was studied. In addition to the flow experiments and calculations of 10 l/min, we also assessed how different CFD models would behave when calculations were performed with a doubled Reynolds number corresponding to human nasal breathing of 20 l/min. The inspiratory phase can be regarded as being more important than the expiratory phase because patients with nasal obstruction usually feel that inspiratory breathing is more difficult. All PIV measurements and CFD calculations were made using the silicone model.

We have provided the comprehensive setup of the study in Supplementary Information (Suppl. Inf.)

2.1. NASAL CAVITY GEOMETRY AND SILICONE MODEL PRODUCTION

The procedure for producing the silicone model of the nasal cavities used in the PIV measurements closely followed the approach previously presented by Hopkins et al. (2000). Pre-operative nasal CBCT scans, with a slice resolution of 0.2 mm, of one adult patient with chronic nasal obstruction and inferior turbinate enlargement without chronic sinusitis, nasal polyps or other pathology were used in our study.

OnDemand3D™ software was used in the processing of the patient CBCT scans with Hounsfield Unit (HU) values from -1000 to -430, as previously described (Valtonen et al., 2018; Valtonen et al., 2020). A Standard Tessellation Language (STL) file, scaled by a factor of 1.85, formed from patient CBCT scans was used to produce a water soluble polyvinyl alcohol (PVA) print. This was then used to create a silicone model (Fig. 1). CBCT scans of the silicone model, with a slice resolution of 0.3 mm, were also taken to create an STL file for CFD calculations. Confirmed from the OnDemand3D™ software’s own scaling function, the same HU values that were used with the patient CBCT scans were applied.

2.2. PIV EXPERIMENTS

The silicone model and laser measurement planes for the PIV measurements are presented in Fig. 2. In addition, comprehensive parameters and setup are presented in the Supplementary Information (Suppl. Inf.). From the fluid dynamic point of view, dimensional similarity between in vivo and in vitro was obtained by matching Reynolds numbers. This resulted in the following flow rate in vitro:

![Fig. 1. The printed negative of the nasal cavities. The anterior parts of the nasal cavities are on the left side. Negatives of the nasal flow passages were printed in separate parts because printer dimensions were limited.](image-url)
Q\textsubscript{\textit{vitro}} = D\textsubscript{\textit{vitro}} \times \nu\textsubscript{\textit{vitro}} = \frac{10^4 \times 1.85 \times 11.7}{16} \text{ l/min} = 13.53 \text{ l/min}

in which \( Q \) is volume flow rate, \( D \) is model scaling compared to conditions in vivo and \( \nu \) is kinematic viscosity. All measurements were gathered with this steady state inspiratory volume flow rate of 0.225 l/s. The silicone model was held in a liquid tank in which constant pressure was achieved by liquid overflowing from the tank.

2.3. CFD CALCULATIONS

CFD calculations were conducted with open source OpenFoam 5.0 software. The flow was assumed to be incompressible. In addition, the same geometry was used as in the PIV experiments. The studied CFD models comprised a laminar model and two turbulent models (\( k-\omega \) and \( k-\omega \) SST). For the inlet, uniform total pressure boundary condition was used. For the outlet, the boundary condition was the PIV experiments’ flow rate of 0.225 l/s. In turbulent cases, a turbulent inlet intensity of 10% was investigated to study the maximal differences between the laminar and turbulent models.

In addition to calculating and measuring with the flow rate of 10 l/min in vivo, CFD calculations with the doubled Reynolds number corresponding to human breathing of 20 l/min were studied. This was conducted by changing the dynamic viscosity without adjusting the other flow properties. The dynamic viscosity was changed instead of volume flow rate to avoid any detectable inlet velocity profile variations stemming from the use of total pressure boundary condition. One calculation took roughly one week to complete in 24 processors.

2.4. DATA ANALYSIS

For the analysis, four coronal cross-sections were chosen: the anterior tip of the inferior turbinate, the anterior tip of the middle turbinate, the posterior part of the inferior turbinate and the nasopharynx (Fig. 3). The Reynolds numbers in these analysed four cross-sections were 308, 212, 155 and 485, respectively. The first three coronal cross-sections of the nasal cavities were divided into three vertical parts and further divided in to left and right sides in order to better illustrate the route of the flow (Fig. 3). The fourth cross-section was only divided into left and right sides.

Time averaged axial mean flow velocity and axial volume flow rate ratios were measured from PIV and calculated from CFD in these cross-sections. These represent the velocity and the distribution of the flow in the nasal cavities. Axial volume flow rate ratios were calculated by dividing local flow rates over summarised total flow rates.

To assess the stress caused by the flow to the boundary of the flow...
and the nasal cavity surface, median wall shear stresses (WSS) were calculated in the same cross-sections from CFD. In the analyses, the origo was located at the nasolabial angle. The numerical post-processing was made with open-source visualisation and data analysis software ParaView 5.0.1.

3. Results

Axial mean flow velocities calculated from laminar CFD showed the highest results in the left nasal cavity’s lower third in the first cross-section (0.33 m/s) and in the middle third in the second cross-section (0.43 m/s) (Table 1) (Fig. 4.a). Corresponding measurements with PIV were 0.34 m/s and 0.39 m/s (Fig. 4.b). In the right nasal cavity, the calculated axial mean flow velocities in laminar CFD were highest in the lower third of the first cross-section (0.45 m/s) and in the lower third of the third cross-section (0.29 m/s). Corresponding measurements with PIV were 0.42 m/s and 0.18 m/s. In the fourth cross-section, the axial mean velocities were equal between laminar CFD and PIV in both the left (0.10 m/s) and right sides (0.15 m/s). The differences in axial mean velocities between the laminar and turbulent (k-ω and k-ω SST) CFD

Table 1
Area averaged mean axial velocities (m/s) in the nose for flow rate of 13.53 l/min in vitro corresponding to human breathing of 10 l/min. The coronal cross-sections (1-4) and division to vertical thirds (lower, middle, upper) area visually presented in Fig. 3. Left and right nasal cavities are analysed separately. The first three cross-sections are analysed in Table 1a. The fourth coronal cross-section was analysed as a whole due to the location behind the nasal septum in Table 1b. In the fourth cross-section, the division is done by using the centre line of the nasal septum as a landmark

<table>
<thead>
<tr>
<th></th>
<th>1st CFD (laminar)</th>
<th>1st CFD (turbulent)</th>
<th>1st PIV</th>
<th>2nd CFD (laminar)</th>
<th>2nd CFD (turbulent)</th>
<th>2nd PIV</th>
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Table 1b.

<table>
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<tr>
<th></th>
<th>4th CFD (laminar)</th>
<th>4th CFD (turbulent)</th>
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</table>
models were small.

The main volume of the flow calculated from CFD in the left nasal cavity’s first cross-section was in the lower third with a ratio of 0.47 (Table 2). The PIV measurement in the same location was 0.48. In the right nasal cavity, the main volume of the flow calculated from laminar CFD was in the lower third of the nasal cavity in all three most anterior cross-sections with ratios ranging from 0.35 to 0.42. Corresponding PIV measurements were from 0.35 to 0.41. In the fourth cross-section, the volume of the flow was equal between laminar CFD and PIV for the left (0.42) and right sides (0.58). The differences in axial volume flow rate ratios between the laminar and turbulent (k-ω and k-ω SST) CFD models were small.

Median wall shear stress was highest in the lower third of the first cross-section at 7.76 Pa (Table 3, Fig. 5). In the second cross-section, median WSS varied from 2.07 to 6.55 Pa and in the third cross-section from 4.02 to 5.97 Pa. In the whole fourth cross-section, median WSS was 2.92 Pa.

CFD calculations with the calculated flow corresponding to the flow of 20 l/min in vivo did not show any considerable differences between the CFD models (Tables 4–5).

### Table 2
Area averaged volume flow rate ratios in the nose for flow rate of 13.53 l/min in vitro corresponding to human breathing of 10 l/min. The coronal cross-sections (1-4) and division to vertical thirds (lower, middle, upper) are visually presented in Fig. 3. Left and right nasal cavities are analysed separately. The first three cross-sections are analysed in Table 2a. The fourth coronal cross-section was analysed as a whole due to the location behind the nasal septum in Table 2b. In the fourth cross-section the division is done by using the centre line of the nasal septum as a landmark.

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<td>0.11</td>
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<tr>
<td>PIV</td>
<td>0.37</td>
<td>0.35</td>
<td>0.06</td>
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### Table 3
Median wall shear stresses (Pa) in the nose for flow rate of 13.53 l/min in vitro calculated from CFD corresponding to human breathing of 10 l/min. The coronal cross-sections (1-4) and division to vertical thirds (lower, middle, upper) are visually presented in Fig. 3. The fourth coronal cross-section was analysed as a whole due to the location behind the nasal septum. The median WSS result for the fourth coronal cross-section was 2.92 Pa.

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4. Discussion

In this study, we have presented numerical comparisons between a mathematical model of nasal airflow (CFD) and the measured flow (PIV) in a realistic nasal cavity acquired from CBCT scans for the first time. CFD and PIV results corresponded well in our study. Moreover, the
The correspondence of CFD calculations between laminar and turbulent ($k$-$\omega$ and $k$-$\omega$ SST) models was found to be even stronger. When comparing CFD with PIV, we found that the results were most convergent in the wider parts of the nasal cavities. In addition, the distribution of the flow volume proved to be convergent between CFD and PIV despite the smaller flow velocities in PIV in some locations. The most notable differences were observed in the narrowest passages of the nasal cavities. The results from both CFD and PIV showed the main flow streaming mainly in the lower and middle thirds of the nasal cavities.

At first, the flow through the nasal cavities was found to be the strongest in the anterior part of the inferior nasal turbinates, after which the flow spread to a vertically wider area (Table 1, Table 2). However, the main flow stayed mainly at the level of the inferior and middle nasal turbinates. The results were convergent between the flow velocity and the distribution of the flow volume. The strongest axial flow could be visually observed mainly in the narrow mid-parts of the nasal cavities (Fig. 4). The shear stresses in various areas may have significance on the subjective feeling of nasal patency. In our study, median wall shear stresses, calculated from CFD, were the highest on the surface of the lower and middle thirds of the nasal cavities (Table 3). These areas contain the inferior and middle nasal turbinates which are also the

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**Table 4**

Area averaged mean velocities (m/s) in the nose for flow rate of 13.53 l/min in vitro corresponding to human breathing of 20 l/min. The coronal cross-sections (1-4) and division to vertical thirds (lower, middle, upper) are visually presented in Fig. 3. Left and right nasal cavities are analysed separately. The first three cross-sections are analysed in Table 4a. The fourth coronal cross-section was analysed as a whole due to the location behind nasal septum in Table 4b. In the fourth cross-section, the division is done by using the centre line of the nasal septum as a landmark.

**Table 4a.**

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<th>2nd CFD (laminar)</th>
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**Table 4b.**

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structures that are most often the reason for the symptoms of nasal blockage caused by swelling (Willatt, 2009). In the posterior parts of the nasal cavities, the median wall shear stresses are more evenly divided. However, a few sudden local structural changes increased wall shear stresses locally as can be seen, for example, in the upper part of the second cross-sections (Fig. 5).

Our CFD and PIV results are somewhat in agreement with the results of previous studies (Doorly et al., 2008; Chung and Kim, 2008; Na et al., 2012; Zubair et al., 2015; Lintermann and Schröder, 2017; Cozzi et al., 2019). The studies from Lintermann et al., Chung et al. and Na et al. all presented similar findings of the flow passing mainly through the lower and middle thirds of the nasal cavities (Chung and Kim, 2008; Na et al., 2012; Lintermann and Schröder, 2017). In the studies by Cozzi et al. and Zubair et al., the results between CFD and PIV had a fair agreement, which is in line with our results (Cozzi et al., 2017; Zubair et al., 2015). A precise comparison between studies is, however, challenging because previous studies have not reported overall numerical comparisons between various CFD models and PIV in the nasal cavities. In addition, the Reynolds numbers, study setups, CFD models and the extent and accuracy of previous studies have varied. Therefore, it remains difficult to assess which CFD model performs optimally in the nasal cavities based on PIV measurements.

CFD succeeded well in our study in all locations with both laminar and turbulent models. The differences between these three models were small, and it is therefore difficult to assess which model obtains the most correct results. In addition, as was previously studied with static pressure measurements in high turbulent conditions (100 l/min in vivo) using stereolithography resin material by Mylavarapu et al. (2009), finding the most convenient turbulent CFD model is also challenging with their approach. Their study showed the k-ω turbulence model achieved the best experimental agreement with an average error of about 20% over all pressure ports along the nasal cavity. The reason for the investigated high flow rate in their study was the insensitivity of the static pressure probes to small values. Therefore, realistic human breathing flow rates are not technically easy to study with pressure measurements along a nasal cavity.

In addition to PIV measurements, Li et al. studied hot-wire anemometer velocity results against CFD results in a nasal cavity model scaled by a factor of 20 (Li et al., 2017). The K-ω CFD model obtained the best RANS model results for flow rates of 33.6 l/min and 66 l/min in vivo. LES and DNS results remained better than any RANS model. However, for human breathing of 10.8 l/min, the laminar model obtained the best results among the RANS models and did not differ much from the LES or DNS models.

In principle, PIV measurements can be made anywhere in the nasal cavity, but the most reliable results are obtained in the middle of the cavities where velocity gradients are usually the smallest. Conversely, pressure measurements, which were out of the scope of our study, are easier to perform at the walls. The differences are also clear in model scaling between these two approaches. PIV measurements should be made with a large scaling to increase measurement resolution, whereas the opposite is better for pressure measurement ranges.

For PIV measurements, the present study geometry of the nasal cavities is one of the most realistic used. In this setup, PVA was found to be challenging to dissolve in water and took more time than expected. Two silicone model processing artefacts left a nasal septum perforation to the level of the second and third cross-section (Fig. 3). These perforations were the result of the challenges faced in the modelling and processing of very narrow structures. However, these perforations did not cause any unexpected disturbances to the CFD calculations. Thus, we interpreted the effect of the perforations as being relatively small from the viewpoint of CFD model validation.

Overall, the PIV results are shown to be reasonably good in the anterior parts of the nasal cavity as well as in the end of the nasal cavities. More distinguishable results are observed, especially in the middle parts of the nasal cavities where the narrowest passages are present. Detailed and obstructed passages of the nasal cavities are generally harder to measure but are ideal from a CFD validation perspective, possessing more details from a clinical perspective. Hence, there exists a trade-off between CFD model validation precision and the accuracy of the studied nasal cavity geometries. Based on the findings of the current study, our view is that when using PIV measurements, simplifications are needed, and wider passages with greater model scaling should be preferred from the study geometry or other similar realistic geometries.

When it comes to PIV measurements, more erroneous laser sheet positioning and a wider range of velocities across the laser sheet thickness emerge as nasal cavity widths decrease. Conversely, infinitely small laser sheet thickness is not an optimal solution either because particles with the slightest off-plane velocities escape the laser sheet between double-frame images. Hence, an optimal value for laser sheet thickness

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depends on laser sheet positioning precision and a ratio between in-plane and out-of-plane velocities. All the aforementioned problems with PIV could, however, be reduced by greater silicone model scaling. Our scaling of 1.85 is in the typical range of the other conducted PIV studies (Dooryl et al., 2008; Chung and Kim 2008; Na et al., 2012; Zubair et al., 2015; Lintermann and Schröder, 2017; Cozzi et al., 2017). In addition to greater scaling, PIV measurements could be conducted in a two-fold way to identify and possibly remove measurement errors and to solve turbulent quantities. At first, experiments should be carried out in purely laminar conditions. In the second part of the measurements, the viscosity of the experiments should be lowered to make the Reynolds number higher corresponding to the actual investigated conditions. Comparisons between the first and second parts of the measurements could solve turbulence quantities more reliably than conventional one-part measurements.

We conducted experiments and calculations with incompressible fluid with constant flow rates. It has been found elsewhere that steady flow assumption is sufficient for most times of the respiratory cycle in PIV measurements of the nasal cavities (Spence et al., 2012). Lee et al. found similar results with unsteady CFD simulations by using LES (Lee et al., 2010). In our study with a steady flow rate, the results remained mostly stationary. However, mean flow unsteadiness was mostly present at the beginning of the end part of the nasal cavities. This phenomenon was more dominant in the left part of the nasal cavities, which was narrower, especially in the upper parts of the cavity.

The quasi-steady flow assumption is usually made with CFD studies. Furthermore, current clinical rhinomanometry results are usually reported without a reference to temporal information. A flow compressibility study in a simplified 2-dimensional geometry claimed unsteadiness of the rhinomanometric results emerging primarily from flow storage effect, which cannot be modelled in the incompressible PIV experiments (Groß and Peters, 2011). To the best of our knowledge, no detailed CFD nasal airflow study with unsteadiness and flow compressibility has been conducted, where the results are simultaneously compared to more simple assumptions. Unfortunately, such studies can only be easily validated with global assessment of the flow without information on the local details. Therefore, compared to PIV experiments, flow compressibility studies are only partly suitable for comparing different CFD models.

Silicone models could be used for experimental compressible studies with global assessment of the flow. The problem is often that silicone models for the PIV experiments are scaled to be larger than conditions in vivo. As a result the measurement area of the rhinomanometric devices used in clinics may not be sufficient. In addition, excessive scaling of the model might affect the interpretation of the rhinomanometric results of the 3D model compared to clinical circumstances.

Fortunately, 3D printing in plastic has been studied as a convenient alternative to silicone models in the global assessment of the flow (Valtonen et al., 2020). The benefit of plastic is cheaper and faster production, although certain technical problems still exist. Large series of 3D printed plastic models in vitro could provide an alternative to PIV experiments in CFD model validation.

CFD could be useful in obtaining a wider understanding of a patient’s subjective feeling of nasal blockage. For example, it might be possible to calculate WSS and pressure losses across the upper respiratory system could be connected to the patient’s subjective feelings on nasal obstruction, although this needs further study. Other affecting variables that must be taken into account in future studies are probably heat and mass transfer from the mucus membrane, which were out of the scope of the current study.

According to the findings of our study, PIV measurements in realistically modelled nasal cavities succeeded acceptably and CFD calculations produced corresponding results with PIV mean flow measurements. Therefore, CFD could be considered as an option in assessing nasal airflow. Currently, CFD calculations are too time-consuming and complex for clinical practice. These calculations should therefore be made faster by orders of magnitude and more automated pre-processing of patient data is also needed.

5. Conclusions

In our study, we found that PIV measurements in realistically modelled nasal cavities succeeded acceptably and CFD calculations produced corresponding results with PIV measurements. The differences between laminar and turbulent CFD model results were found to be small in most parts of the nasal cavities. This finding supports the suitability of laminar flow approximation in studying natural human breathing in the nasal cavities. However, greater model scaling is necessary for better validations with PIV and comparisons of competing CFD models. CFD of nasal CBCT scans could be considered an additional option for rhinomanometry in assessing and analysing nasal airflow and the effect of pathologies on it. Currently, CFD has its limitations and it needs to be modified in order to be more straightforward for clinical use.

Data Availability

All data are available on request.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

Acknowledgements

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resp.2020.103508.

References


Three-Dimensional Measurements in Assessing the Results of Inferior Turbinate Surgery

Valtonen O, Ormiskangas J, Harju T, Rautiainen M, Kivekäs I

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Three-Dimensional Measurements in Assessing the Results of Inferior Turbinate Surgery

Olli Valtonen, MD1,2*, Jaakko Ormiskangas, MSc (Tech.)2,3*, Teemu Harju, MD, PhD1,2, Markus Rautiainen, MD, PhD1,2, and Ilkka Kivekäs, MD, PhD1,2

Abstract
Objectives: Acoustic rhinometry is widely used in evaluating patients with nasal congestion, but it only has a partial correlation with patient symptoms. The use and focus of cone beam computed tomography (CBCT) scans are mainly on the paranasal sinuses and less on the nasal cavities. Therefore, information acquired from CBCT scans is not used to its full extent. In our present study, we have studied patients with enlarged inferior turbinates. Our aim was to investigate and compare the use of 3D volumetric measurements and cross-sectional area measurements taken from CBCT scans to results obtained from acoustic rhinometry.

Material and methods: In total, 25 patients with enlarged inferior turbinates were studied. CBCT scans were obtained preoperatively and at twelve months postoperatively. 3D volumetric and cross-sectional area measurements were compared to results from acoustic rhinometry, the visual analogue scale (VAS) and Glasgow Health Status Inventory (GHSI) questionnaires.

Results: A statistically significant change in 3D volume and cross-sectional area was measured in the anterior part of the inferior turbinate and surrounding air space after inferior turbinate surgery. VAS and GHSI results had mild correlations with the 3D volume and cross-sectional area measurements of the anterior part of the inferior turbinate. Acoustic rhinometry correlated with the air space 3D volume measurements in the anterior part.

Conclusions: Fully utilized CBCT scans provide more comprehensive and accurate information. Furthermore, 3D analysis of the inferior turbinates provides valuable information and more precise measurements compared to acoustic rhinometry.

Keywords
3D, volumetry, nasal cavity, turbinate, RFTA

Introduction

Today, the 2 most common objective methods for assessing nasal congestion are acoustic rhinometry and rhinomanometry.1,2 Both methods have proven to be fast and mostly reliable in measuring dimensions and breathing resistance in the nose. The use of these methods has, however, been problematic, especially when the patient’s subjective sensations of nasal blockage or patency are taken into account. Moreover, the Visual Analogue Scale (VAS) and other symptom questionnaires have failed to show a consensus of correlation with acoustic rhinometry or rhinomanometry.3

In previous studies, the assessment of the volume of the nasal cavities has been mostly done using information gained from acoustic rhinometry. However, acoustic rhinometry, especially in the posterior regions, is known to overestimate the dimensions of the nasal cavity.4–7 Indeed, in a study by Cankurtaran et al, acoustic rhinometry was found to have overestimated the volume of the nasal cavity airway.

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Email: olli.valtonen@pshp.fi
by more than 20%. To date, however, the actual 3D volumetric measurements from pre- and postoperative CT or magnetic resonance imaging (MRI) scans and any possible benefits compared to acoustic rhinometry in patients with operated nasal cavities have not been extensively studied.

Inferior turbinate surgery with different methods is one of the main surgical procedures for treating nasal congestion. Usually, acoustic rhinometry and different subjective assessment methods are chosen to evaluate the effects of these operations on the circumstances in the nasal cavity. In previous studies, the postoperative follow-up times have been fairly short, and the most commonly used time span between pre- and postoperative data gathering has varied from a few weeks to a few months. The long-term effects of these operations on volumetric dimensions, acoustic rhinometry results, patient symptoms and their correlations from 1 or more years of follow-up have not as yet been studied sufficiently.

In the present study, the aim was to study and compare the use of 3D volumetric measurements accompanied with cross-sectional area measurements to those results obtained from acoustic rhinometry. Moreover, the potential of 3D volumetric and cross-sectional area measurements in reflecting the patients’ subjective sensations was also studied using VAS and quality of life (QOL) scores.

**Materials and Methods**

In the present study, 26 patients with chronic nasal obstruction were included. These patients had enlarged inferior

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Figure 1. An example of the preoperative patient CBCT scans (A) with marked inferior turbinates (red) used as a basis for the production of the inferior turbinate 3D models (B) which were used in the 3D volumetric measurements. Corresponding examples of the postoperative patient CBCT scans (C) and the produced inferior turbinate 3D models (D) are also presented.
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Turbinates and underwent radiofrequency thermal ablation (RFTA) treatment (Sutter RF generator BM-780 II, Freiburg, Germany) to the inferior turbinates on both sides. The patients were scanned preoperatively and at twelve months postoperatively with cone beam computed tomography (CBCT) (Planmeca Max, Planmeca, Helsinki, Finland). CBCT data were saved to a file in Digital Imaging and Communications in Medicine (DICOM) format and downloaded to OnDemand3D™ software (version 1.0, CyberMed, Inc., Yuseong-gu, Daejeon, South Korea). OnDemand3D™ software was used to perform the 3D volumetric and cross-sectional area measurements.

On both sides, the volume of the whole inferior turbinate was 3D modeled and measured from the pre- and postoperative CBCT scans (Figure 1). The same measurements were performed on the operated anterior part of the inferior turbinate and the air space surrounding the turbinate (Figure 2). The anterior part consisted of an area from 5 to 20 mm posterior from the anterior peak of the inferior turbinate. Hounsfield Unit (HU) values from −429 to 400 were used to measure the inferior turbinate. These values were obtained using the measuring software’s own scaling function. HU values from −1000 to −430 were used for the measurement of the pneumatized area according to previous studies. Some 3D modeling artefacts, included to the 3D measurements by the software, were manually excluded from the structures of interest.

We also used CBCT scans to measure the coronal cross-sectional areas from both the inferior turbinates and the air spaces surrounding the inferior turbinates. The measurement

Figure 2. An example of the preoperative patient CBCT scans (A) with marked air spaces (blue) surrounding the operated anterior parts of the inferior turbinates used as a basis for the production of the air space 3D models (B) which were used in the 3D volumetric measurements. Corresponding examples of the postoperative patient CBCT scans (C) and the produced air space 3D models (D) are also presented.
of the cross-sectional areas started 5 mm and ended 50 mm posterior from the anterior peak of the inferior turbinate. The distance between each measuring point was 5 mm. For these measurements, we used the Smart Pen function of OnDemand3D™ with some manual corrections.

For both the volumetric and cross-sectional area measurements, the uppermost limit of the region of interest (ROI) was set at the lowest level of the middle turbinate. The nasal cavity floor was used as the lowest level of the ROI. Using the OnDemand3D™ software, the volumetric and cross-sectional area measurements of the pre- and postoperative CBCT scans took approximately 7 to 10 hours per patient.

The patients were asked to fill in the VAS questionnaire preoperatively and at 12 postoperatively in order to assess the severity of nasal obstruction. To assess the effects of a health problem on quality of life, the patients were asked to fill in the Glasgow Health Status Inventory (GHSI) questionnaire. Acoustic rhinometry (Acoustic rhinometer A1, GM Instruments Ltd, Kilwinning, UK) was also performed pre- and postoperatively. An encompassing analysis of the acoustic rhinometry and subjective questionnaire results has been presented in a previous study.12 The acoustic rhinometry tests without adrenaline and the results from both MCA2 and V2-5 were used in this study.

Before the final data analysis, 1 patient was excluded from the study due to extensive artefacts in the CBCT scans caused by dental fillings which prevented 3D measurements. Thus, 25 patients were included in the present study’s data analysis. In addition, with regard to only the correlation analysis, 1 patient had to be excluded due to missing acoustic rhinometry measurements. This resulted in a total of 24 patients being included in this analysis.

All the data were analyzed using SPSS (version 26, IBM, Armonk, NY, USA) software. The Wilcoxon signed-rank test was used to analyze the statistical significance of the measurement results. The Spearman correlation test was used for correlation analysis.

Institutional Review Board approval for the study (R13144) was obtained from the Ethics Committee of Tampere University Hospital, Tampere, Finland.

### Results

The preoperative median total volume from the combined left and right inferior turbinate was 11.7 cm³. The median total volume postoperatively was 9.3 cm³. In the anterior 5 to 20 mm of the inferior turbinate, the preoperative inferior turbinate total volume of 4.2 cm³ decreased postoperatively to 3.0 cm³. Corresponding volumetric results for the pneumatized area in the anterior part increased from 2.3 to 3.4 cm³. The changes between preoperative and postoperative volumes were statistically significant in all the measured areas (Table 1).

When the preoperative and postoperative measurements were analyzed together, comprising 48 cases in total, the volumetric measurements of the pneumatized nasal cavity in the anterior part of the measured region correlated with V2-5 results from acoustic rhinometry (0.523, P < .001) and with VAS scores (−0.279, P < .05) (Figure 3). Turbinate volume correlated with VAS (0.390, P < .001) and QOL (−0.433, P < .001) scores in the anterior part of its volume. However, the measurements of the whole length of the inferior turbinate or the changes in it did not correlate with the other parameters. Moreover, the volume changes in the anterior part of the inferior turbinate or the air space

| Table 1. Median volumetric pre- and postoperative results. Turbine volume represents the inferior turbinate as a whole and the anterior part measurements are presented in the 5 to 20 mm results (n = 25). The results are shown from both sides separately and the total results represent the combined results from both the left and right sides. The lower quartile (Q25) and upper quartile (Q75) are shown with the median. The statistical significance of the change between pre- and postoperative results, analysed with Wilcoxon signed-rank test, is also disclosed. |
|---|---|---|---|---|---|---|---|
| **Turbinate** | Left (pre) | Right (pre) | Total (pre) | Left (post) | Right (post) | Total (post) | Total (change) |
| Median volume (cm³) | 4.9 | 5.6 | 11.7 | 4.8 | 4.5 | 9.3 | −1.7 |
| Q25 | 3.8 | 4.6 | 9.0 | 3.9 | 3.5 | 8.0 | −3.3 |
| Q75 | 6.8 | 7.2 | 13.1 | 6.3 | 5.7 | 11.2 | 0.0 |

<table>
<thead>
<tr>
<th><strong>Turbinate (5-20 mm)</strong></th>
<th>Left (pre)</th>
<th>Right (pre)</th>
<th>Total (pre)</th>
<th>Left (post)</th>
<th>Right (post)</th>
<th>Total (post)</th>
<th>Total (change)</th>
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<td>3.0</td>
<td>−1.2</td>
</tr>
<tr>
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<td>1.4</td>
<td>1.6</td>
<td>3.3</td>
<td>1.3</td>
<td>1.3</td>
<td>2.7</td>
<td>−2.0</td>
</tr>
<tr>
<td>Q75</td>
<td>2.6</td>
<td>2.6</td>
<td>4.9</td>
<td>2.0</td>
<td>1.6</td>
<td>3.3</td>
<td>−0.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Air (5-20 mm)</strong></th>
<th>Left (pre)</th>
<th>Right (pre)</th>
<th>Total (pre)</th>
<th>Left (post)</th>
<th>Right (post)</th>
<th>Total (post)</th>
<th>Total (change)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median volume (cm³)</td>
<td>1.4</td>
<td>1.2</td>
<td>2.6</td>
<td>1.6</td>
<td>1.9</td>
<td>3.4</td>
<td>0.8</td>
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<tr>
<td>Q25</td>
<td>0.9</td>
<td>0.7</td>
<td>2.0</td>
<td>1.2</td>
<td>1.5</td>
<td>2.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Q75</td>
<td>1.8</td>
<td>1.6</td>
<td>3.4</td>
<td>2.2</td>
<td>2.3</td>
<td>4.4</td>
<td>1.9</td>
</tr>
</tbody>
</table>

_PP_
surrounding it did not correlate with changes in the other parameters.

The main cross-sectional area changes from pre- to postoperative values were found in the region of the operated anterior part of the inferior turbinate and the pneumatized area surrounding it (Figure 4). These changes were also statistically significant. Some smaller cross-sectional area changes with a statistical significance were also found in the posterior regions of the inferior turbinate. When the pre- and postoperative measurements were analyzed together, the cross-sectional area measurements correlated with VAS and QOL scores in the most anterior measurement points but did not correlate with the other parameters (Table 2). The cross-sectional area changes did not correlate with changes in the other parameters.

Discussion

At present, CBCT scans are widely used as part of the examination of patients with symptoms of nasal congestion. The information gained from these scans, however, is not used to its full extent. In our present study, we demonstrate the use of 3D volumetric measurements combined with cross-sectional area measurements to assess the results of operative treatment in the inferior turbinates from CBCT scans. These methods proved to be accurate in measuring the inferior turbinates and the surrounding air space and in assessing the changes in them. Moreover, the measurements produced both objective and descriptive results on the effects of the RFTA treatment.

In the whole length of the inferior turbinate, the change from pre- to postoperative volume was −15%. A corresponding volume change for the anterior part of the inferior turbinate was −28% and +41% for the surrounding air space. These findings reflect well the given treatment’s effect on the operated turbinates, where the anterior part of the inferior turbinate is treated.

Some changes in the inferior turbinate and the surrounding air cross-sectional area measurements were also found in the middle and posterior measuring points (Figure 4). In the middle regions, for example, both the cross-sectional area of the turbinates and the air had decreased. In addition, even though the most posterior regions of the inferior turbinate were not operated, the effect of the operation seemed to be parallel, though statistically significant at a mild level, to the anterior part of the inferior turbinate. It is possible therefore that these changes could be due to a neural or vascular process in the inferior turbinate and possibly even in the whole nasal cavity. These findings suggest that other compensatory changes might occur in the other parts of the nasal cavity after inferior turbinate surgery that could subsequently have an effect on the patients’ sensation of nasal obstruction or patency. However, our study focused only on the inferior turbinates and their surroundings, and therefore further studies are required to assess this possible phenomenon.
We found correlations between the volume of the pneumatized area around the anterior part of the inferior turbinates and both the V2-5 results from acoustic rhinometry and VAS scores, although these correlations were mild (Figure 3). Both subjective assessment methods had a mild correlation with the anterior turbinate volume measurements. These findings are in line with the observations of previous studies, where the subjective measurement methods did not produce strong correlating results with objective clinical assessment methods. In these previous studies, VAS scale results correlated with results that varied from no correlation to fairly good correlation when compared to acoustic rhinometry or rhinomanometry.

We are aware of only a few studies in which the volumetric measurements of the nasal cavity structures taken from CT or MRI scans have been used alongside results from acoustic rhinometry to assess operated nasal cavity volumes. Kilavuz et al studied electrocautery and

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**Table 2.** Cross-sectional area correlation with VAS and QOL scores in the area of the anterior part of the inferior turbinate for both pre- and postoperative results (n = 48). The correlation coefficient with VAS and QOL is shown for every cross-sectional area measuring point from the anterior part (5-20 mm) of the inferior turbinate. The statistically significant results, analysed with Spearman’s rho test, are presented with an asterisk.

<table>
<thead>
<tr>
<th>Cross-sectional area correlation with VAS and QOL</th>
<th>Turbinate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 mm</td>
</tr>
<tr>
<td>VAS</td>
<td>−0.408**</td>
</tr>
<tr>
<td>QOL</td>
<td>0.280*</td>
</tr>
</tbody>
</table>

*P < .05, **P < .01.

---

**Figure 4.** Cross-sectional area changes in both inferior turbinate and surrounding air in every measuring point (n = 25). The total results represent the combined left and right nasal cavity results. The distance represents the measuring point distance from the anterior peak of the inferior turbinate. Statistically significant inferior turbinate or air space changes per every measuring point, analysed with Wilcoxon signed-rank test, are marked with an asterisk.

*P < .05, **P < .01.
The limitation of the methods we used in our study is that they are still time consuming. However, combined information from the 3D volumetric method and cross-sectional area measurements provide an objective method for assessing the results of inferior turbinate surgery and other operations of the nasal cavity. As previously mentioned, the assessment results are more precise than those provided by acoustic rhinometry, especially in the mid and posterior parts of the nasal cavity.

Today, the 3D volumetric method combined with cross-sectional area measurements are only applicable for study purposes, and more studies are needed to adjust and speed up the process. The comprehensive assessment of nasal cavity anatomy, changes to it and the effect they have on nasal cavity airflows and patient symptoms will most likely require studies that are carried out using 3D modeling software that can 3D model the airflow conditions and the effect on the mucous membrane.

Conclusions
A significant 3D volume and cross-sectional area decrease was measured in the anterior part of the inferior turbinate after RFTA treatment, whereas the surrounding air increased significantly. The treatment led to some possible compensatory changes, especially in the middle and posterior parts of the inferior turbinates. Overall, 3D volumetric and cross-sectional area measurements had mild to moderate correlation with other parameters. In evaluating the effects of inferior turbinate surgery, 3D volumetric and cross-sectional area measurements proved to be accurate. CBCT scans can be used more comprehensively as a diagnostics tool and for further analytics.

Declaration of Conflicting Interests
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Data availability
All data are available on request.
References


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Computational fluid dynamics assessed changes of nasal airflow after inferior turbinate surgery

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Inferior turbinate
Mucous membrane

\textbf{ABSTRACT}

\textbf{Objective:} To demonstrate how Computational Fluid Dynamics (CFD) simulations can reveal important airflow changes in the nasal cavities due to surgical interventions.

\textbf{Material and methods:} The steady inspiratory airflow of eight patients was studied pre- and postoperatively with heat transfer from the mucous membrane by performing CFD calculations to patient specific cone beam computed tomography (CBCT) images. Eight patients with the largest distance from pre- and postoperative mean changes in inferior turbinate volumetry and Visual Analogue Scale (VAS) results were selected.

\textbf{Results:} Calculated CFD heat transfer results from the anterior parts of the inferior turbinates, where surgical interventions were performed, decreased significantly. The heat transfer results were in line with VAS changes.

\textbf{Conclusion:} Surgical interventions reduced heat transfer in the operated parts of the inferior turbinates and were in line with VAS changes. CFD is an option in assessing patient well-being as a function of airflow parameters from mucous membrane with larger data sets. The limitations of the study were the small sample size and the preliminary nature of the study.

1. Introduction

Currently, acoustic rhinometry and rhinomanometry are the most well-established objective methods for assessing nasal congestion and the nasal cavities. Unfortunately, a patient’s subjective assessment of nasal congestion does not necessarily correlate with the findings of these objective methods. Another drawback is that information obtained from rhinomaneometric studies is not detailed enough for the studying and planning of nasal surgeries. Acoustic rhinometry obtains a two-dimensional (2D) cross-sectional area measurement along the nasal cavities, whereas rhinomanometry obtains a global assessment of the flow. Its most commonly used form is active anterior rhinomanometry, where flow is studied separately for both sides of the nasal cavities. The separate results are then calculated together to obtain total nasal airflow resistance. An excellent review of the above methods has been published (Vogt et al., 2010). However, information obtained from rhinomanometric studies is not detailed enough for studying and planning the nasal surgeries.

Cone beam computed tomography (CBCT) imaging provides full three-dimensional (3D) information on the nasal cavities, which is not obtained in rhinomanometric studies. However, the information obtained from CBCT imaging is not used to its full extent in clinical practice. Furthermore, postoperative CBCT information from patients is scarce, as in daily practice these images are not usually gathered. The information obtained from CBCT scans can be used for CFD calculations to comprehensively study nasal airflow in the nasal cavities. In addition, CFD calculations can be used to obtain information that is useful in assessing the subjective nasal patency of patients. A literature review of these methods has been conducted (Radulesco et al., 2019). Unfortunately, CFD calculations are time-consuming and require technical expertise. Therefore, many challenges still remain for the studies of nasal airflow. These challenges have been previously described in a number of reviews (Zubair et al., 2012; Kim et al., 2013; Quadrio et al., 2014).

In the present study, we aim to demonstrate how CFD calculations can be used to study the effects of inferior turbinate surgery from CBCT...
images acquired preoperatively and at one-year follow-up.

2. Material and methods

2.1. Surgical process and follow-up visit

In the present study, 8 patients from a cohort of 25 patients with chronic nasal obstruction were included. The included patients had no chronic sinusitis, nasal polypos or other pathologies. All 25 patients had enlarged inferior turbinates and had undergone radiofrequency thermal ablation (RFTA) treatment (Sutter RF generator BM-780 II, Freiburg, Germany) to the anterior parts of the inferior turbinates on both sides. The surgical process is described in detail in a study by Harju et al. (2018). The patients were evaluated prior to surgery and at one year after surgery. During both visits, patients were scanned with cone beam computed tomography (CBCT) (Planmeca Max, Planmeca, Helsinki, Finland). The following imaging parameters were used: 0.2 mm CT slice thickness, voxel size 0.2 mm, 90 kVp, 8 mA and 4 s radiation time. Additionally, patients were asked to fill out the Visual Analogue Scale (VAS) questionnaire pre- and postoperatively to assess the severity of nasal obstruction on both sides simultaneously. The VAS questionnaire assessed patient experiences from the previous 7 days. Institutional Review Board approval for the study (R13144) was obtained from Tampere University Hospital Ethics Committee, Tampere, Finland.

2.2. CBCT data and CFD calculations

Our aim was to demonstrate the use of CFD calculations in the evaluation of changes in flow variables between pre- and postoperative conditions in inferior turbinate surgery. At present, this process requires a lot of time and computational resources. Therefore, from the whole cohort of 25 patients, we chose only eight patients, who represented varying extremities of objective and subjective responses. The eight patients were subsequently divided into four groups based on air space volume changes surrounding the anterior 5–20 mm of the inferior turbinates between the pre- and postoperative CBCT scans and changes in VAS during the one-year follow-up. For the analysis, the groups (two patients per group) were called Group 1 (large VAS changes and large volumetric changes), Group 2 (large VAS changes and small volumetric changes), Group 3 (small VAS changes and large volumetric changes) and Group 4 (small VAS changes and small volumetric changes) (Table 1).

The CBCT data of the chosen patients were saved to a file in Digital Imaging and Communications in Medicine (DICOM) format and downloaded to OnDemand3D™ software (version 1.0, CyberMed, Inc., Yuseong-gu, Daejeon, South Korea). The software was then used to create a 3D model the air space in the nasal cavities from the nostrils to the nasal nuses were excluded from the study. Additionally, any small 3D modelling artefacts included in the 3D models by the software, were manually excluded from the structures of interest. The prepared 3D models were then saved in Standard Tessellation Language (STL) format. When necessary, any small artefacts possibly still found in the 3D models, were removed from the STL files with the open-source modelling software Blender v.2.82a (Blender Foundation).

The STL files were then meshed with open source OpenFOAM 5.0 software’s utilities blockMesh and snappyHexMesh. The meshing of wall boundary layers was made using absolute size refinements, whereas hexahedral elements were used for the inner geometry with similar cell sizes in all regions. Mesh sizes were between four and six million cells in all calculations.

The same OpenFOAM 5.0 software was used for CFD calculations with a laminar and incompressible flow assumption. In previous studies, laminar calculations have been found to be suitable for nasal airflow. Uniform total pressure condition was applied in the nostrils. To study the airflow in the nasal cavities, we used a constant inspiratory flow rate that was also patient specific by determining the flow rate as a function of gender and weight (Garcia et al., 2009)

\[
\text{For males: } \dot{V} = (1.36 \pm 0.10) M^{0.644(1.02)} \\
\text{For females: } \dot{V} = (1.89 \pm 0.40) M^{0.52(0.66)}
\]

where \( \dot{V} \) is flow rate (litres per minute) and \( M \) is weight in kilograms. Steady-state inspiratory flow rates used in the calculations were twice the mean flow rate for each patient defined from Eq. (1). In addition, equal flow rates were used pre- and postoperatively for each patient. All calculations were conducted with heat transfer from the rigid walls with no-slip condition. Ambient air had a temperature of 20 °C. For our heat transfer calculations, the mucous membrane surface temperatures \( T_{\text{mucous}} \) were adjusted to have a mean temperature of approximately 32 °C according to the following Equation:

\[
q = h_m (T_{\text{body}} - T_{\text{mucous}})
\]

where \( q \) is a local heat flux (W/m²) from the mucous membrane surface to airflow; \( T_{\text{body}} \) is body temperature of 310.15 Kelvin (K); \( T_{\text{mucous}} \) is a local mucous membrane surface temperature and \( h_m \) is a uniform heat transfer coefficient across the mucous membrane in all positions of the nasal cavities. Coefficient \( h_m \) was experimentally adjusted to 50W/(m²K) to have similar mucous membrane surface temperatures as in the clinical measurements by Lindemann et al. (2002). Across the whole nasal cavity, Eq. (2) obtains approximately a mean mucous membrane surface temperature of 32 °C. When no local heat transfer is present, Eq.

<table>
<thead>
<tr>
<th>Group 1</th>
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<th>Group 3</th>
<th>Group 4</th>
</tr>
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<tbody>
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<td>Vol. change large</td>
<td>VAS change large</td>
<td>Vol. change small</td>
</tr>
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<td>Patient</td>
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</tr>
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<td>VAS change</td>
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<td>-8.0</td>
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<tr>
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</tr>
</tbody>
</table>
2.3. Data analysis

In order to assess patients’ local sensitivity to pressure losses, we calculated the mean pressure loss from the nostrils to the mean pressure along the whole surface of the inferior turbinates from the CFD calculations (Fig. 1). Then, total heat transfer was calculated in the operated anterior 25 mm of the inferior turbinates. Furthermore, total pressure loss and total heat transfer from the nostrils to the nasopharynx were calculated to assess the total effects of the inferior turbinate surgeries. Nasopharynx results were measured vertically at the bottom level of inferior turbinates airways since not all patients had much downstream geometry from the nasopharynx. In all our cases, however, mesh geometry was extended 50 mm downstream from the nasopharynx for computational reasons. The analysis was made to both sides of the nasal cavities simultaneously as was the treatment and patient VAS assessment. The Wilcoxon signed-rank test was used to analyse the statistical significance of the results. The numerical post-processing of the acquired CFD data was made with the open source visualization and data analysis software ParaView 5.0.1.

3. Results

In the anterior 25 mm of the inferior turbinate, the median heat transfer postoperatively was less in all groups, except for Group 4 which had small VAS and volumetric changes. Preoperatively, the median heat transfer from the anterior 0–25 mm of the inferior turbinates for all 8 patients was 0.91 Watts (W), whereas the median heat transfer postoperatively was 0.65 W. The changes between preoperative and postoperative heat transfer for all eight patients were statistically significant (p < 0.05). This was the direct result of the enlarged postoperative airway volumes in those regions. (Table 2).

The median air temperatures in the nasopharynx postoperatively were also less in all groups, except for Group 4. The median air temperature in the nasopharynx for all 8 patients was 31.1 °C preoperatively and 30.9 °C postoperatively. (Table 3) The median pressure losses from ambient to inferior turbinates as well as to the nasopharynx were postoperatively less in Groups 1 and 3, which had large volumetric changes. However, the opposite was true for Groups 2 and 4, which had small volumetric changes. (Tables 4–5) The preoperative mucosal heat fluxes and pressure results are visually presented for Patient 1 (Figs. 2–3).

4. Discussion

In this study, we have presented the CFD results from a subset of inferior turbinate surgeries both preoperatively and at twelve months postoperatively. Our results showed statistically significant reduced heat transfer in the anterior 25 mm of the inferior turbinates postoperatively. Similarly, several virtual studies of turbinate surgery have shown decreased total heat transfer in most cases (Lee et al., 2016; Na et al., 2012). We are unaware of previous studies with patients that have reported reduced heat transfer results for inferior turbinate surgery pre- and postoperatively. Previously, CFD studies have been reported after concomitant septorhinoplasty or septoplasty and turbinate surgery in patients with turbinate hypertrophy and septum deviation. Casey et al. (2017) examined preoperative patients and healthy controls but did not evaluate the effects of the surgical procedure. In their study, they found that healthy subjects had a significantly higher middle airflow than preoperative patients on the most obstructed side. Sullivan et al. (2014) conducted a study pre- and postoperatively without healthy controls. They found that a surface area where heat flux exceeds 50 W/m² on the obstructed side correlated best with VAS and NOSE survey results. Kimbell et al. (2013) reported pre- and postoperative CFD results for those patients who did not have nasal cycle effects in CT images. By contrast, Gaberino et al. (2017) studied patients with nasal cycle effects pre- and postoperatively. Nasal cycle effects were corrected computationally and correlations between CFD variables and subjective scores improved.

All the above-mentioned studies assessed VAS results unilaterally and mostly compared CFD results from the more obstructed side to the corresponding unilateral instantaneous VAS or longer-term NOSE survey results. This can be understood to be the most meaningful comparison since many patients were operated with septoplasty. Our patients underwent treatment in the anterior parts of the inferior turbinates on both sides. Similarly, VAS assessment from the previous seven days was made simultaneously on both sides. The choice of correct VAS

Fig. 1. The preoperative nasal cavities of Patient 1. Inferior turbinate regions are marked in white. Nasopharynx measurement position is marked with crosslines.
The nasal cavity. Smaller heat transfer in the anterior parts leads to higher heat transfer in the posterior parts, which, in turn, stems from colder air flowing downstream in the nasal cavities.

For pressure losses, local pressure at the inferior turbinates and across the whole nasal cavities alike, groups with large volumetric changes had smaller median pressure losses postoperatively, whereas for groups with small volumetric changes the opposite was true (Tables 4–5). Pressure loss results did not correlate with VAS changes.

However, it could be assumed that pressure losses would be smaller after inferior turbinate surgery for larger cohorts since the increase of volume leads to smaller pressure losses, as happens in more simplified structures. In previous studies, strong correlations between sinus pathologies (Valtonen et al., 2018) or rhinomanometric results (Andre et al., 2009) and the patients’ subjective assessment have not been found.

Calculated heat transfer is subject to assumptions about nasal assessment remains challenging since many factors can affect the instantaneous and longer-term subjective feelings of nasal patency.

The median heat transfer in the anterior 25 mm of the inferior turbinates only increased in the group with small volumetric and small VAS changes and decreased in all the other groups. Heat transfer results were in line with VAS changes. However, no statistical analysis was performed due to the small sample size. This resulted mostly from larger air volumes in regions that reduce heat transfer. In the total heat transfer results, the ratios of changes between pre- and postoperative conditions were smaller than in the heat transfer results from the anterior parts of the inferior turbinates. This result stems from the inferior turbinate heat transfer only contributing to a part of the total nasal heat transfer. Furthermore, the procedure also causes redivision of the heat transfer in the nasal cavity. Smaller heat transfer in the anterior parts leads to higher heat transfer in the posterior parts, which, in turn, stems from colder air flowing downstream in the nasal cavities.
temperature is 37°C along the nasal cavity. Furthermore, our approach assumes that mucosal temperatures along the nasal cavity (Lindemann et al., 2002). In their study, mucosal temperatures were measured statistically different mucosal temperatures as a function of heat transfer (Eq. 2). An example of this is visually presented (Fig. 4).

Pressure difference from ambient to nasopharynx. The statistical significance of the change between pre- and postoperative results was analysed with Wilcoxon signed-rank test.

Table 4

<table>
<thead>
<tr>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
</tr>
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<tbody>
<tr>
<td>VAS change</td>
<td>VAS change</td>
<td>VAS change</td>
<td>VAS change</td>
</tr>
<tr>
<td>large</td>
<td>large</td>
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<td>small</td>
</tr>
<tr>
<td>Vol. change large</td>
<td>Vol. change small</td>
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<td>Vol. change small</td>
</tr>
<tr>
<td>Patient 1</td>
<td>Patient 3</td>
<td>Patient 5</td>
<td>Patient 7</td>
</tr>
<tr>
<td>Patient 2</td>
<td>Patient 4</td>
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<td>Patient 8</td>
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Post/Pre | Median | Median | Median | Median |
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<th></th>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Pre [Pa]</td>
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</tr>
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<td>31.9</td>
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</tr>
<tr>
<td>Change [Pa]</td>
<td>-10.7</td>
<td>-0.4</td>
<td>20.1</td>
<td>0.6</td>
</tr>
<tr>
<td>(p – 0.94)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Post/Pre</td>
<td>0.24</td>
<td>1.19</td>
<td>0.75</td>
<td>1.41</td>
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</table>

Table 5

<table>
<thead>
<tr>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
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<tbody>
<tr>
<td>VAS change</td>
<td>VAS change</td>
<td>VAS change</td>
<td>VAS change</td>
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<tr>
<td>large</td>
<td>large</td>
<td>small</td>
<td>small</td>
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<tr>
<td>Vol. change large</td>
<td>Vol. change small</td>
<td>Vol. change large</td>
<td>Vol. change small</td>
</tr>
<tr>
<td>Patient 1</td>
<td>Patient 3</td>
<td>Patient 5</td>
<td>Patient 7</td>
</tr>
<tr>
<td>Patient 2</td>
<td>Patient 4</td>
<td>Patient 6</td>
<td>Patient 8</td>
</tr>
</tbody>
</table>

Post/Pre | Median | Median | Median | Median |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<td>Pre [Pa]</td>
<td>14.7</td>
<td>17.9</td>
<td>17.6</td>
<td>29.2</td>
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<tr>
<td>Post [Pa]</td>
<td>20.0</td>
<td>21.2</td>
<td>14.6</td>
<td>6.2</td>
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<tr>
<td>Change [Pa]</td>
<td>10.4</td>
<td>0.4</td>
<td>14.6</td>
<td>17.7</td>
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<tr>
<td>(p – 0.84)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Post/Pre</td>
<td>0.28</td>
<td>1.46</td>
<td>0.79</td>
<td>1.19</td>
</tr>
</tbody>
</table>

Our results assume that inspiratory flow rates are independent from surgery volumetric changes and that patients breathe as much pre- and postoperatively as corresponding healthy individuals. It can be expected that this assumption holds true for a large majority of patients. However, some studies have assumed that postoperative pressure loss was equal to the preoperative pressure loss which resulted in reduced flow rates preoperatively (Kimbell et al., 2013; Sullivan et al., 2014; Gaberino et al., 2017).

Our assumption was that the heat transfer properties of mucous membrane are exactly the same pre- and postoperatively. Heat transfer in the anterior part of the inferior turbinate was less postoperatively than preoperatively which is to be expected when air volumes become greater and flow gradients at the mucous membrane surfaces are reduced. The median total heat transfer also decreased in almost all investigated groups. Additionally, reduced postoperative heat transfer at the anterior parts led to increased heat transfer at the posterior parts of the nasal cavities. At the same time, VAS scores were better postoperatively. These results could support the hypothesis that certain receptors that are sensitive to nasal congestion are concentrated more on the posterior parts of the nasal cavity or even the nasopharynx. In the

mucosal temperatures. We approached these calculations by not assuming a constant mucous membrane temperature along the nasal cavity, but by varying nasal mucosal temperatures as a function of heat transfer itself (Eq. 2). An example of this is visually presented (Fig. 4). This approach was a numerical fit to the experimental mucosal temperatures along the nasal cavity (Lindemann et al., 2002). In their study, Lindemann et al. measured statistically different mucosal temperatures along the nasal cavity. Furthermore, our approach assumes that mucosal temperature is 37°C while local heat transfer from the mucous membrane is not present. Unfortunately, temperature data are very scarce along the nasal cavity and few studies have been made. Further, areas with negligible heat transfer are hard to measure. It could be that our assumption is not completely true either and results in too much variation in nasal mucosal temperatures along the nasal cavities. Except for Na et al. (2012), other studies have mostly used constant mucous membrane surface temperatures. Although further studies with larger datasets will probably improve nasal mucosal temperature calculations but may have a similar form as our Eq. 2.

Our results assume that inspiratory flow rates are independent from
previous literature, Meusel et al. (2010) reported the uniform distribution of menthol-sensitive receptors in the nasal cavity. In future studies, one possibility could be to include the modelling of mucous membrane properties coupled with CFD calculations.

This study presents a patient series with clinically homogenic inferior turbinate hypertrophy, and all other nasal diseases were excluded. Radiological heterogeneity in a geometric variation of the nasal cavities exists among our patients and within our study groups, as it does generally in all populations. Therefore, it is very important that the results of surgery are evaluated between pre- and postoperative scans of the same patient.

The limitations of the study are the small sample size and the preliminary nature of the study. In the groups with small volumetric changes in the anterior parts of the inferior turbinates, small overall

Fig. 2. The preoperative pressure loss (Pa) results from ambient to the nasal mucosa for Patient 1.

Fig. 3. The preoperative nasal mucosa heat fluxes (W/m²) for Patient 1.
contractions of the nasal cavities might be possible postoperatively and may have had a slight effect on the pressure drop results, as was the case at 12-month follow-up in the present study. In future, better surgical planning could enhance surgical operations and unexpected results would become less common.

In future studies, larger patients cohorts will be needed. However, in these studies, many regional CFD results along the nasal cavities often correlate strongly with other regions in close proximity. Thus, this makes a localized psychophysical model of patient well-being as a function of flow quantities hard to develop. One solution could be to assume that local sensitivity to airflow quantities is uniform in large parts of the nasal cavities. One could even assume VAS and Quality of life (QOL) results are a function weighted sum of flow variables at certain regions of the nasal cavities. The method used in the present study can obtain CFD results that reveal changes in flow quantities due to inferior turbinate surgery. Therefore, our presented method can be used for assessing larger cohorts of patients and for developing psychophysical models of nasal congestion.

Currently, the information obtained from CBCT scans is not used to its full extent in clinical practice. In most cases, CBCT scans are used in the examination of patients with chronic rhinosinusitis. The information provided by CBCT scans can, however, be used in CFD calculations to comprehensively study nasal airflow in the nasal cavities. The results of the present study demonstrate that CFD can assess differences in airflow quantities as a result of volumetric changes due to inferior turbinate surgery. These methods provide future possibilities for assessing nasal congestion and its effect on the well-being of patients.

5. Conclusions

Surgical interventions reduced heat transfer in the operated parts of the inferior turbinates and were in line with patient VAS changes. This study shows that CFD is an option in assessing patient well-being as a function of airflow parameters from mucous membrane with larger data sets. The results support the hypothesis that nasal congestion – sensitive receptors might be more concentrated at the posterior parts of the nasal cavities. CFD could therefore have potential in the planning and evaluation of nasal surgical procedures in future. The limitations of the study are the small sample size and the preliminary nature of the study.

Conflict of Interest Statement

The authors declare that there is no conflict of interest.

Acknowledgement

The author(s) received financial support from the Finnish ORL-HNS Foundation, Finland and Tampere Tuberculosis Foundation, Finland for the research, authorship, and/or publication of this article.

References


Fig. 4. The preoperative nasal mucosal temperatures (°C) for Patient 1.


Computational fluid dynamics calculations in inferior turbinate surgery: a cohort study

Ormiskangas J, Valtonen O, Harju T, Rautiainen M, Kivekäs I

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Computational fluid dynamics calculations in inferior turbinate surgery: a cohort study

Jaakko Ormiskangas1,2 · Olli Valtonen1,3 · Teemu Harju1,3 · Markus Rautiainen1,3 · Ilkka Kivekäs1,3

Abstract
Purpose To investigate how the results of nasal computational fluid dynamics (CFD) simulations change due to inferior turbinate surgery and how the results correlate with patient specific subjective assessment and volumetric results in the nasal cavities.

Methods The steady inspiratory airflow of 25 patients was studied pre- and postoperatively with heat transfer from the mucous membrane by performing CFD calculations to patient-specific nasal cone beam computed tomography images. These results were then compared to the severity of the patients’ nasal obstruction Visual Analogue Scale (VAS) and Glasgow Health Status Inventory assessments, and acoustic rhinometry measurements.

Results Total wall shear forces decreased statistically significantly \((p < 0.01)\) in the operated parts of the inferior turbinates. Patients’ subjective nasal obstruction VAS assessment changes between the pre- and postoperative conditions correlated statistically significantly \((p = 0.04)\) with the wall shear force results.

Conclusion Inferior turbinate surgery lead to decreased total wall shear force values postoperatively. Changes in subjective nasal obstruction VAS results against total wall shear force changes between the pre- and postoperative conditions were statistically significant. CFD data have a potential to be used for the evaluation of nasal airflow.

Keywords CBCT · CFD · Nasal cavity · Inferior turbinate · Mucous membrane

Introduction
Currently, clinicians have only rudimentary objective tools at their disposal for assessing the nasal cavities and nasal congestion. Unfortunately, the subjective assessment of nasal patency and quality of life provided by patients does not always correlate with current objective methods [1, 2]. At present, the most detailed objective information is obtained from computed tomography or cone beam computed tomography (CBCT). CBCT imaging provides full three-dimensional (3D) information on the nasal cavities, which is not obtained in rhinomanometric studies. In addition to the clinical objective methods currently used, a further detailed 3D analysis of the nasal cavities and corresponding nasal airflow can be obtained using Computational Fluid Dynamics (CFD) calculations. These calculations are based on flow governed by Navier–Stokes equations, which are solved using numerical methods. CFD calculations can also be used to obtain information that is useful in assessing the subjective nasal patency of patients. Literature reviews of these methods has recently been conducted [3, 4].

Previously, nasal airflow CFD studies have been conducted using various approaches. CFD calculations are subject to boundary conditions and modelling assumptions which can affect the results. The important boundary conditions include mucous membrane properties and surface temperatures, turbulence modelling and nasal airflow volume flow rates. Most previous studies have investigated inspiratory nasal airflow with constant patient specific- volume flow rates either pre- and postoperatively or preoperatively against healthy controls. The subjective responses of patients are usually analysed against calculated CFD results, such as...
heat transfer and wall shear stresses (WSS), which are then reported as meaningful objective CFD measures. Most studies of nasal airflow have used heterogenous patient cohorts in which septoplasty is often performed [5–9]. In these studies, the best correlations have been found between visual analogue scale (VAS) assessment from the most obstructed side of the nasal cavities and CFD results from the same side. Similar correlations have also been observed with NOSE surveys and VAS assessment against CFD results.

In the present study, we aim to investigate how CFD calculations can model patient specific VAS and quality of life (QOL) values as a function of flow variables in inferior turbinate surgery. In addition, acoustic rhinometry and volumetric measurements are investigated and compared to CFD results.

Materials and methods

Surgical procedure and follow-up visits

In the present study, 25 patients with chronic nasal obstruction caused by enlarged inferior turbinates were included. All included patients underwent radiofrequency thermal ablation (RFTA) treatment (Sutter RF generator BM-780 II, Freiburg, Germany) to the anterior parts of the inferior turbinates on both sides. The exclusion criteria of the study were chronic sinusitis, nasal polyps or other nasal pathologies. The surgical process is described in detail elsewhere [10]. The volumetric changes in the nasal cavities between the pre- and postoperative conditions of the surgical process have been previously reported by Valtonen et al. [11]. In the present study, patients were evaluated prior to surgery and at one year after surgery. During both visits, the patients were scanned with cone beam computed tomography (CBCT) (Planmeca Max, Planmeca, Helsinki, Finland). The following imaging parameters were used: 0.2 mm CT slice thickness, voxel size 0.2 mm, 90 kVp, 8 mA and 4 s radiation time. Additionally, patients were asked to fill out the Visual Analogue Scale (VAS) questionnaire both pre- and postoperatively to simultaneously evaluate the severity of the nasal obstruction on both sides of the nasal cavities. The VAS questionnaire assessed patient experiences from the previous 7 days (on a scale of 0–10, with 0 meaning completely open and 10 completely blocked). Furthermore, to assess the QOL, patients were also asked to fill in the Glasgow Health Status Inventory (GHSI) questionnaire from the previous 7 days. The GHSI questionnaire contains 18 questions measured with a 5-point Likert scale. These scores are then transformed to a scale ranging from 0 to 100. Higher scores in the GHSI indicate an enhancement in patient well-being and QOL. Additionally, acoustic rhinometry V2-5 cm (Acoustic rhinometer A1, GM instruments Ltd, Kilwinning, UK) results were also investigated pre- and postoperatively without vasoconstriction. However, one patient had missing acoustic rhinometry results. Therefore, acoustic rhinometry results were analysed with 24 patients. Institutional Review Board approval for the study (R13144) was obtained from Tampere University Hospital Ethics Committee, Tampere, Finland.

CBCT data and CFD calculations

The aim of the present study was to study the VAS and GHSI assessments of patients as a function of the flow variables obtained from CFD calculations between the pre- and postoperative conditions in inferior turbinate surgery. The CBCT data of the chosen patients were saved to a file in Digital Imaging and Communications in Medicine (DICOM) format and downloaded to OnDemand3D™ software (version 1.0, CyberMed, Inc., Yuseong-gu, Daejeon, South Korea). The software was then used to create a 3D model of the air space in the nasal cavities from the nostrils to the nasopharynx. For 3D modelling, Hounsfield unit (HU) values from −1000 to −430 were used to represent the air space according to previous studies [2, 11–14]. The maxillary, frontal and sphenoidal sinuses were excluded from the study. Additionally, any small 3D modelling artefacts included in the 3D models by the software, were manually excluded from the structures of interest. The prepared 3D models were then saved in Standard Tessellation Language (STL) format. When necessary, any small artefacts still found in the 3D models were removed from the STL files using the open-source modelling software Blender v2.82a (Blender Foundation). Isolated air regions with no possible airflow were also removed and were not included in the CFD calculations or volumetric measurements.

The STL files were then meshed with open source OpenFOAM 5.0 software’s utilities blockMesh and snappyHexMesh. The meshing of wall boundary layers was made using absolute size refinements, whereas hexahedral elements were used for the inner geometry with similar cell sizes in all regions. Mesh sizes were between four and six million cells in all calculations.

The same OpenFOAM 5.0 software was used for CFD calculations with a laminar and incompressible flow assumption. In previous studies, laminar calculations have been found to be suitable for nasal airflow. Uniform total pressure condition was applied in the nostrils. To study the airflow in the nasal cavities, we used a constant inspiratory flow rate as a function of gender and weight [15]

For males: \( \dot{V} = (1.36 \pm 0.10)M_0^{0.44\pm0.02} \)

For females: \( \dot{V} = (1.89 \pm 0.40)M_0^{0.32\pm0.06} \) (1)
where \( V \) is flow rate (litres per minute) and \( M \) is weight in kilograms. The steady-state inspiratory flow rates used in the calculations were twice the mean flow rate for each patient defined from Eq. (1). In addition, equal flow rates were used pre- and postoperatively for each patient. All calculations were conducted with heat transfer from the rigid walls with no-slip condition. Ambient air had a temperature of 20 °C. For our heat transfer calculations, the mucous membrane surface temperatures \( T_{\text{mucous}} \) were adjusted to have a mean temperature of approximately 32 °C according to the following Equation:

\[
q = h_m (T_{\text{body}} - T_{\text{mucous}})
\]  

(2)

where \( q \) is a local heat flux (W/m²) from the mucous membrane surface to airflow; \( T_{\text{body}} \) is body temperature of 310.15 Kelvin (K); \( T_{\text{mucous}} \) is a local mucous membrane surface temperature and \( h_m \) is a uniform heat transfer coefficient across the mucous membrane in all positions of the nasal cavities. Coefficient \( h_m \) was experimentally adjusted to 50W/(m²K) to have similar mucous membrane surface temperatures as in the clinical measurements by Lindemann et al. [16]. Across the whole nasal cavity, Eq. (2) obtains approximately a mean mucous membrane surface temperature of 32 °C. However, when no local heat transfer is present, Eq. (2) obtains a mucous membrane temperature of 37 °C. To complete the calculation of a single 3D model, one week was required with 24 processors. The heat transfer calculation procedure presented here is similar to the study by Ormiskangas et al. [14].

**Data analysis**

In a previous study, most volumetric changes from inferior turbinate surgeries have been found to occur in the anterior parts comprising 5–20 mm of the inferior turbinates [11]. Therefore, total heat transfer and magnitudes of wall shear forces were calculated at the surface of the mucous membrane in the operated anterior parts of the inferior turbinates (Fig. 1). The anterior part comprised 5–20 mm area posterior from the anterior peak of the inferior turbinate. The uppermost limit of the inferior turbinates was set at the lowest level of the middle turbinates. All values were then integrated separately into total values in the operated anterior 5–20 mm parts of the inferior turbinates.

Pressure losses along the nasal cavities were calculated from the nostrils to the nasopharynx to assess the total effects of the inferior turbinate surgeries. Nasopharynx results were measured vertically at the bottom level of inferior turbinates airways since not all patients had much downstream geometry from the nasopharynx. In all our calculated cases, our mesh geometry was extended 50 mm downstream from the nasopharynx for computational reasons. The analysis was made to both sides of the nasal cavities simultaneously, as was the treatment and patient VAS assessment and GHSI questionnaire. The Wilcoxon signed-rank test was used to analyse the statistical significance of the results between the pre- and postoperative conditions. Spearman’s rank correlation was used to analyse univariate correlations between all results. The numerical post-processing of the acquired CFD data was performed with the open-source visualization and data analysis software ParaView 5.0.1.

**Results**

In the anterior 5–20 mm of the inferior turbinates, statistically significant decreases were found in total wall shear forces (\( p < 0.01 \)) between the pre- and postoperative conditions (\( n = 25 \)). However, no significant changes were found in the heat transfer results in the anterior parts of the inferior turbinates or in any of the results from the rest of the nasal cavity. (Table 1) The pre- and postoperative wall shear stresses are visually presented for one patient (Fig. 2). In the anterior parts of the inferior turbinates, a statistically significant negative correlation was found between total wall shear force values (\( p < 0.001 \)) and volumetrically measured airway volumes (\( n = 50 \)) when all values were pooled (pre- and postoperative, \( n = 50 \)). In the same area, no statistically significant correlation was found between heat transfer and volumetrically measured airway volumes. Furthermore, there were no statistically significant correlations between total wall shear forces and heat transfer in the operated parts of the inferior turbinates against acoustic rhinometry V2–5 cm results. For patients’ subjective assessment no statistically significant correlations were found between total wall shear force or total heat transfer in the operated parts against nasal obstruction VAS or GHSI assessments (Table 2).
In the anterior parts of the inferior turbinates, a statistically significant negative correlation was found between total wall shear force value changes against volumetrically measured air volume changes ($n=25$) between the pre- and postoperative conditions ($p<0.001$). In the same area, heat transfer changes against air volume changes were not statistically significant. Furthermore, no statistically significant correlations were found between total wall shear force or heat transfer changes against acoustic rhinometry V2–5 cm changes. For patients’ subjective assessment, there was a statistically significant positive correlation in the anterior parts of the inferior turbinates between total wall shear force changes against nasal obstruction VAS changes ($p=0.04$). No other statistically significant results were found between total wall shear force or heat transfer changes against nasal obstruction VAS or GHSI changes. (Table 3) The pre- and postoperative mucosal heat fluxes are visually presented for one patient (Fig. 3).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Pre- and 12-month postoperative Computational Fluid Dynamics results and their changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated CFD results and changes</td>
<td>Wall shear forces in the anterior 5–20 mm parts of the inferior turbinates [N]</td>
</tr>
<tr>
<td>Preoperative median (IQ25–IQ75)</td>
<td>3.22<em>10$^{-4}$ (2.53</em>10$^{-4}$ to 4.25*10$^{-4}$)</td>
</tr>
<tr>
<td>Postoperative median (IQ25–IQ75)</td>
<td>1.62<em>10$^{-4}$ (1.36</em>10$^{-4}$ to 2.27*10$^{-4}$)</td>
</tr>
<tr>
<td>Change median (IQ25–IQ75)</td>
<td>−1.12<em>10$^{-4}$ (−2.54</em>10$^{-4}$ to −6.03*10$^{-6}$)</td>
</tr>
<tr>
<td>Change $p$-value</td>
<td>$&lt;0.01$</td>
</tr>
</tbody>
</table>

Both sides of the nasal cavities are analysed together. The Wilcoxon signed-rank test was used to calculate two-sided $p$-values.

| Table 2 | Univariate Spearman correlations between calculated CFD values (total wall shear forces and total heat transfer) from the anterior 5–20 mm parts of the inferior turbinates and the subjective and volumetric measures |
|---|---|---|---|---|---|---|---|
| Spearman’s rho | Wall shear forces against VAS | Heat transfer against VAS | Wall shear forces against GHSI | Heat transfer against GHSI | Wall shear forces against V2–5 cm | Heat transfer against V2–5 cm | Heat transfer against air volume |
| $p$-value | 0.19 | 0.17 | −0.08 | −0.01 | −0.26 | 0.12 | −0.68 | −0.24 |
| | 0.18 | 0.24 | 0.56 | 0.94 | 0.07 | 0.41 | <0.001 | 0.09 |

Both sides of the nasal cavities are analysed together. The table also presents $p$-values ($n=50$). Acoustic rhinometry results V2–5 cm had one missing patient ($n=48$).
Further, no statistically significant correlations were found between pressure losses from ambient to nasopharynx ($n=50$) and their changes ($n=25$) between the pre- and postoperative conditions against subjective nasal obstruction VAS and GHSI measures. However, a statistically significant positive correlation was found between pressure loss changes ($n=25$) along the nasal cavity against total wall shear force value changes in the operated parts of the inferior turbinates between the pre- and postoperative conditions. (Table 4) The pre- and postoperative pressure results are visually presented for one patient (Fig. 4).

### Table 3
Univariate Spearman correlations between changes in calculated CFD values (total wall shear forces and total heat transfer) from the anterior 5–20 mm parts of the inferior turbinates and changes in subjective and volumetric measures

<table>
<thead>
<tr>
<th></th>
<th>Wall shear forces against VAS</th>
<th>Heat transfer against VAS</th>
<th>Wall shear forces against GHSI</th>
<th>Heat transfer against GHSI</th>
<th>Wall shear forces against V2–5 cm</th>
<th>Heat transfer against V2–5 cm</th>
<th>Wall shear forces against air volume</th>
<th>Heat transfer against air volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spearman’s rho</td>
<td>0.40</td>
<td>0.25</td>
<td>−0.19</td>
<td>0.06</td>
<td>−0.24</td>
<td>0.12</td>
<td>−0.65</td>
<td>−0.36</td>
</tr>
<tr>
<td>p-value</td>
<td>0.04</td>
<td>0.23</td>
<td>0.38</td>
<td>0.77</td>
<td>0.27</td>
<td>0.58</td>
<td>&lt;0.001</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Changes in CFD values are calculated by subtracting preoperative values from 12-month postoperative values. Both sides of the nasal cavities are analysed together. The table also presents $p$-values ($n=25$). Acoustic rhinometry results V2–5 cm had one missing patient ($n=24$)

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### Table 4
Univariate Spearman correlations between calculated CFD pressure loss from ambient to nasopharynx against subjective measures and total wall shear stresses in the anterior 5–20 mm parts of the inferior turbinates

<table>
<thead>
<tr>
<th></th>
<th>Pressure loss along the nasal cavity against VAS ($n=50$)</th>
<th>Pressure loss along the nasal cavity against GHSI ($n=50$)</th>
<th>Pressure loss changes along the nasal cavity against VAS changes ($n=25$)</th>
<th>Pressure loss changes along the nasal cavity against GHSI changes ($n=25$)</th>
<th>Pressure loss changes along the nasal cavity against changes in wall shear forces in the anterior 5–20 mm parts of the inferior turbinates ($n=25$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spearman’s rho</td>
<td>0.02</td>
<td>0.04</td>
<td>0.16</td>
<td>0.04</td>
<td>0.64</td>
</tr>
<tr>
<td>p-value</td>
<td>0.86</td>
<td>0.79</td>
<td>0.45</td>
<td>0.86</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Changes in CFD values are calculated by subtracting preoperative values from 12-month postoperative values. Both sides of the nasal cavities are analysed together. The table also presents $p$-values ($n=50, n=25$)
Discussion

In this study, we have presented the CFD results and air volumes and corresponding acoustic rhinometry results from inferior turbinate surgeries both preoperatively and at 12 months postoperatively for what was to our knowledge the largest cohort of patients to date. The aim of inferior turbinate surgery is to reduce turbinate volumes and increase airway volumes in the operated parts. Our CFD results indicate statistically significant decreases in total wall shear forces in the anterior parts of the inferior turbinates postoperatively. Furthermore, statistically significant negative correlations were found between total wall shear forces and volumetrically measured absolute air volumes in the operated parts as well as in their changes between the pre- and postoperative conditions.

In the previous literature, Kimbell et al. [5] evaluated patients who had undergone septoplasty and found that average WSS increased in the obstructed side of the nose postoperatively. However, that study used a different study setting to the one used in our study. For example, in their study, average WSS was calculated from the whole obstructed cavity and the patient-specific pressure drop across the nasal cavities was assumed to be equal between the pre- and postoperative conditions. Furthermore, statistically significant negative correlations were found between total wall shear forces and volumetrically measured absolute air volumes in the operated parts as well as in their changes between the pre- and postoperative conditions.

For patients’ subjective assessment, our results reveal there were statistically significant total wall shear force changes in the anterior parts of the inferior turbinates against VAS changes (n = 25) between the pre- and postoperative conditions. Based on our results, it is unclear whether smaller wall shear force values contribute to better VAS subjective improvement because of smaller pressure drops along the nasal cavity or because of mechanical subjective sensing of reduced wall shear forces at the surface mucous membrane in the anterior parts of the nasal cavities. As wall shear forces act as a mechanical force on the surface of the mucous membrane, it also affects the mechanical sensing of the nasal airflow. Our nasal obstruction VAS changes against pressure drop results from ambient to nasopharynx did not obtain as significant results as the decreased wall shear forces in the anterior parts of the inferior turbinates.

Several virtual studies of turbinate surgery have, in most cases, shown decreased total heat transfer [17–19]. In virtual studies, artificial bilateral theoretical surgery is performed, and the effects of the surgery are evaluated computationally. Similarly, for real life patients, our pilot study [14] reported reduced heat transfer results in the operated parts for inferior turbinate surgery postoperatively. In the present study, the heat transfer in the operated parts did not decrease significantly. With a greater number of patients, however, our results could have possibly shown statistical significance in those results. In this study, similar negative correlations were found in the anterior parts of the inferior turbinates between heat transfer against absolute air volumes and their changes between the pre- and postoperative conditions. However, no statistical significance was found.

Previously, the results of other pre- and postoperative CFD studies have been reported after concomitant septorhinoplasty or septoplasty and turbinate surgery in patients with turbinate hypertrophy and septum deviation. In those studies, the CFD results were usually analysed for the whole nasal cavities separately for the most obstructed side and for the more unobstructed side. These studies have shown increased heat fluxes or total heat transfer from the most obstructed side of the nose postoperatively [5–8]. Sullivan et al. [6] conducted a study pre- and postoperatively without Fig. 4 The pre- (A) and postoperative (B) pressure loss (Pa) results from ambient to the nasal mucosa for one patient
healthy controls. They reported increased total heat transfer and heat fluxes postoperatively in the most obstructed side. In addition, they also reported a surface area, where heat flux exceeds 50 W/m² and peak heat flux. The best heat transfer correlations were obtained with surface areas against subjective measures. Other studies have reported heat fluxes but not the heat transfer rates reported in the present study. Kimbell et al. [5] reported pre- and postoperative heat fluxes for patients (n = 10) from a larger cohort who did not have nasal cycle effects in CT images. In contrast, Gaberino et al. [7] studied patients with nasal cycle effects pre- and postoperatively. Heat fluxes and surface area, where heat flux exceeds 50 W/m², were reported. Nasal cycle effects were corrected computationally and correlations between CFD variables and subjective scores improved. Na et al. [8] studied bilateral septoturbinateplasty (n = 8) and found a correlation between the NOSE scores and with an increase in surface heat flux from the most obstructed side.

In all the above-mentioned studies, it is natural that septoplasty operations led to a more uniform airflow distribution between the nasal cavities. Therefore, heat fluxes increased postoperatively in the most obstructed side. Furthermore, volume flow rates across the nasal cavities increased postoperatively, as it is assumed that postoperative pressure loss was equal to the preoperative pressure loss, resulting in reduced flow rates preoperatively [5–8]. However, with this assumption, the surgical procedure itself affects the calculated preoperative volume flow rates and preoperative CFD results. This effect can also be partly observed in heat transfer results, which are different from those in the present study. Furthermore, in other studies, analysis is evaluated on a greater surface area compared to the anterior parts of the inferior turbinates where our surgical operations were performed.

Our study indicates reduced heat transfer in the operated parts postoperatively but without statistical significance. In our results, it was assumed that inspiratory flow rates are independent from the volumetric changes caused by surgery and that patients breathe as much pre- and postoperatively as corresponding healthy individuals as a function of gender and weight. It can be expected, therefore, that this assumption holds true for a large majority of patients without excessive nasal deformities.

Casey et al. [9] examined preoperative patients and healthy controls but did not evaluate the effects of the surgical procedure. In their study, a constant volume flow rate of 15 l/min was assumed for both patients and healthy controls. Preoperative patients and healthy controls were defined from VAS scores. The study found that preoperative patients had smaller average heat flux in the most obstructed side than healthy controls. Furthermore, they also found that healthy subjects had a significantly higher middle airflow than preoperative patients on the most obstructed side. In our study, the results in the middle parts of the nasal cavities were not analysed separately. It is probable that septum deviations affected their results compared to our cohort. Since inferior turbinate surgery increases airway volumes and airflow in the inferior parts, middle airflow and corresponding heat transfer could be expected to decrease without septum deviations. Our results were concentrated on the inferior turbinate region where the surgical operations were performed. In future, middle airflow regions could be investigated in more detail in studies with larger cohorts.

In most other studies, NOSE scores obtained greater or similar CFD correlations than nasal obstruction VAS scores against CFD variables [5–7, 9]. In our study, general QOL results were collected from the GHSI questionnaire instead of from NOSE surveys. It remains unclear, however, why our GHSI questionnaire did not have comparable correlations as VAS results against objective CFD measures. It might be that the patient’s septoplasty operations contributed to the patients’ QOL more than the similar bilateral surgical operations performed in our patient cohort. Casey et al. [9] reported that a stronger correlation was found between NOSE survey results against VAS results from the most obstructed side than from the more unobstructed side. Our patient cohort were different and the surgical operations were bilateral.

In previous studies [5–7, 9], instantaneous patient VAS results were investigated unilaterally while the other side of the nose was blocked. This is, however, different from CFD calculations, where the nasal airflow is bilateral. It is challenging to evaluate how well patients’ subjective assessment changes from natural breathing conditions to an instantaneous unilateral subjective assessment of the severity of nasal obstruction. In our study, we did not use instantaneous nasal obstruction VAS assessment separately for both sides of the nasal cavities. Instead, the patients’ simultaneous nasal congestion VAS assessment from both sides of the nasal cavities was collected from the previous 7 days. The choice of different VAS assessment is challenging and depends greatly on the patient cohort studied.

To the best of our knowledge, our study had the most clinically homogenous patient cohort in CFD studies to date. Furthermore, our surgical procedure and patients’ subjective assessment of the severity of nasal obstruction differ in several important ways from previous study settings. Our surgical procedure was concentrated on the anterior parts of the inferior turbinates. Therefore, the operated parts were smaller and the surgical procedures performed were more similar than septoplasty patients have previously undergone. In our results, the correlations between VAS changes and heat transfer changes in the operated parts were not statistically significant. However, wall shear force value changes in the operated parts had significant correlations against patients’ subjective assessment. Based on the findings of our
study, wall shear force changes could be at least as informative as heat transfer in the patients’ subjective assessment of the severity of nasal obstruction. Future studies should be concentrated on studying and reporting these results in more detail.

**Conclusion**

Inferior turbinate surgeries in the operated anterior parts of the inferior turbinates lead to decreased total wall shear force values postoperatively. Changes in subjective nasal obstruction VAS results against total wall shear force changes in the operated parts between the pre- and postoperative conditions were statistically significant. CT imaging information could be useful in future for performing CFD calculations in clinical practice. CFD data have a potential to be used for evaluation of nasal airflow.

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**Data availability** All data are available on request.

**Declarations**

**Conflict of interest** The authors declare that there is no conflict of interest.

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