Nasal Breathing Assessment Using Computational Fluid Dynamics: An Update from the Rhinologic Perspective

Thomas Hildebrandt, MD[1] Werner Johannes Heppt, MD[2]

[1] Independent Researcher, Zurich, Switzerland
[2] Department of Otorhinolaryngology–Head and Neck Surgery, Facial Plastic Surgery, Academic Teaching Hospital, Staedtisches Klinikum, Karlsruhe, Germany

Facial Plast Surg 2024;40:331–335.

Address for correspondence Werner Johannes Heppt, MD, Department of Otorhinolaryngology–Head and Neck Surgery, Facial Plastic Surgery, Academic Teaching Hospital, Staedtisches Klinikum Karlsruhe, Moltkestr. 90, 76133 Karlsruhe, Germany (e-mail: wheppt@web.de).

Abstract

An objective assessment of nasal breathing is currently insufficiently achievable. The application of computational fluid dynamics for this purpose is increasingly gaining attention. However, the suggested specific frameworks can differ considerably. To the best of our knowledge, there is not yet a widely accepted clinical usage of computational fluid dynamics. In this article, selected aspects are addressed that might be crucial for future development and possible implementation of computational fluid dynamics in rhinology.

Keywords
- computational fluid dynamics
- statistical shape model
- nasal breathing
- flow field
- wall shear stress
- intranasal airflow

For successful surgery of the nasal framework, preoperative evaluation of nasal breathing is essential. At present, however, this only involves assessing the general patency of the nasal cavity. In the clinical context, objective criteria for distinguishing between normal and impaired nasal breathing exclusively include global parameters such as the total nasal resistance measured by rhinomanometry or the inspiratory peak flow. In addition, cross-sectional areas are examined. The limitations of this relatively basic approach become evident in practice. Frequently it does not meet the clinical requirements due to inconsistencies between the patient's complaints, findings, and the measurement results.[1–4]

Technological advancements have made it possible to use image data obtained through radiological diagnostics of the paranasal sinuses for numerical simulation of intranasal airflow during nasal breathing. This method, known as computational fluid dynamics (CFD), has been established in the industry for years and is increasingly of interest in medical research, yet it is finding tentative applications in rhinology.[5,6] It allows for calculation of any flow parameters with high spatial and temporal resolution in complex geometries, such as the nasal cavity.

This article aims to reflect the latest insights on the application of CFD in rhinology, primarily from the practitioner's perspective. Technical details receive limited attention.

Background

The terms CFD and numerical flow simulation can be used interchangeably. They denote procedures that enable calculation of flow parameters in tortuous geometries when analytic solutions are not feasible. Predominantly, a so-called finite volume method (FVM) is employed.

The mathematical model of CFD refers to a system of partial differential equations, which are called Navier–Stokes equations. They are based on the conservation laws of momentum, energy, and mass. To manage computational effort for flows with possible, not solely, laminar characteristics, turbulence models are commonly utilized.

CFD provides a flow field that can represent any desired parameter with high temporal and spatial resolution. The subsequent visualization is key for flow analysis and understanding higher-order relationships in very complex simulations that address multiple parameters.[7]

article published online January 10, 2024

Issue Theme Nasal Airway Evaluation; Guest Editor: Rui Xavier, MD, PhD

Thieme Medical Publishers, Inc., 333 Seventh Avenue, 18th Floor, New York, NY 10001, USA

DOI https://doi.org/10.1055/s-0043-1777838.
ISSN 0736-6825.

The methods of numerical flow simulation have been extensively tested and have demonstrated reliability and sufficient accuracy in various practical contexts. Thus, when using software with a well-established reputation, in specific cases valid results can be accomplished without extensive experimental testing.

CFD Workflow with Respect to Rhinology

The application of CFD in rhinology is appealing because imaging of the paranasal sinuses, including the nasal cavity, is routinely performed in the cases in which impaired nasal breathing is the predominant symptom. Subsequently, a complete dataset representing the considered anatomical structures is available in a Digital Imaging and Communications in Medicine (DICOM) format.

For reliable simulation outcomes, a minimum image resolution aligning with the requirements for navigated surgery is recommended.[8,9]

The acquired data can be used for three-dimensional reconstruction of the nasal cavity after semiautomated segmenting of the cross-sectional images from the nasal entrance to the choanae. This is followed by discretization of the selected flow domain by creating a mesh comprising polyhedral subdomains. Including the paranasal sinus airway is generally not necessary, as the flow rate within them is negligibly small. Depending on the location and the specific application, various types of polyhedra may be used. The choice of the mesh and its structure plays a crucial role in the accuracy and stability of the simulation (►**Fig. 1**).

Prior to calculation, mathematical and physical modeling must be performed, which includes specifying the boundary conditions. In our experience, it has proven effective for intranasal airflow simulations to set either a constant driving pressure difference or a constant flow rate that corresponds to resting respiration. Further assumptions involve rigid walls, the "no-slip" condition at the wall surface, and incompressible fluid behavior—justified by a Mach number smaller than 0.1. The assumed air density is $1.225\,kg/m^3$, and the dynamic air viscosity is set at 1.789×10^{-5} kg/ms.

For simulation, the CFD solver uses iterative approaches to approximate a solution. During this process, fluid flow parameters are updated continuously until the desired convergence criteria are met. Based on our observations, we believe that steady-state calculations in conjunction with a turbulence model can sufficiently reflect the dynamics of intranasal airflow and meet medical evaluation purposes.[10] Consequently, elaborate advanced procedures such as transient calculation, large eddy simulation (LES), or direct numerical simulation (DNS) might be dispensable in the scope of nasal breathing assessment.

Finally, postprocessing including visualization and analysis is performed, which is crucial for understanding the results. Examination of the velocity and pressure field, along with the wall shear stress (WSS) pattern, holds special clinical significance (►**Fig. 2**). However, in individual cases, it may also be useful to consider the temperature and humidity of the breathed air.

►**Fig. 3** provides a graphical overview of the CFD workflow.

Rethinking the Characterization of Nasal Airflow

Inextricably linked to assessment of nasal breathing is the question: What constitutes nasal breathing? As noted earlier, the main criterion defining the quality of nasal respiration currently hinges on the nasal cavity's total patency. Various methods such as rhinomanometry, cross-sectional area, and inspiratory peak flow measurements are employed to quantify this.[2,4] Consequently, treatment plans for impaired nasal breathing mainly align with these metrics despite the inherent limitations of global parameters. The need to broaden the theoretical framework becomes evident when one takes into

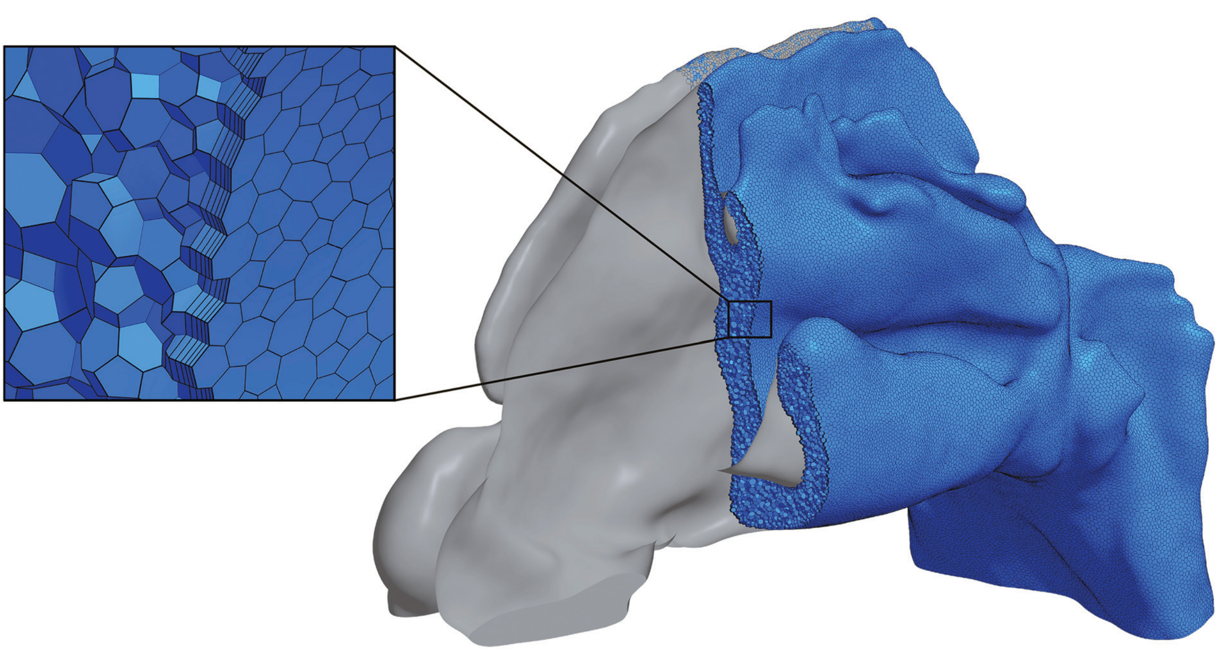

Fig. 1 Meshed flow domain of a left nasal cavity.

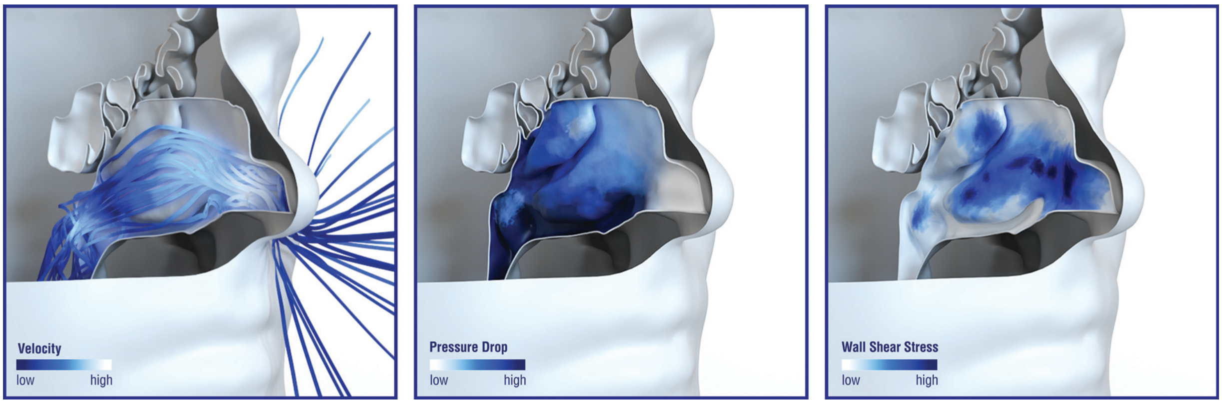

Fig. 2 Illustrated visualization of color-coded inspiratory flow parameters projected onto the left lateral nasal wall. From left to right: streamlines with flow velocity, pressure drop, wall shear stress distribution.

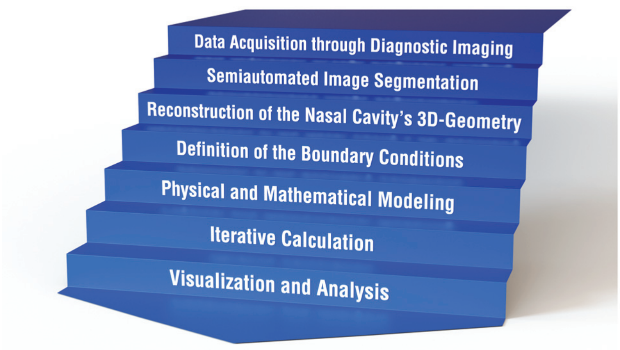

Fig. 3 Rhinology-related workflow of computational fluid dynamics.

account the variety of anatomical and physiological conditions that facilitate normal nasal breathing. The key conditions might be outlined as follows[11]:

- An approximately symmetrical, slitlike flow domain, with a normally configured isthmus area serving as bulk flow formation structure.
- Low but sufficient total nasal resistance.
- Healthy mucous membrane with a normal liquid film.
- Intact erectile tissues and structures.
- Optimal support for the flexible nasal sidewalls.

The intricate interplay of numerous conditions can be succinctly encapsulated as an overall adequate bidirectional interaction between the flowing air and the inner lining, providing a novel and comprehensive understanding of healthy nasal breathing. We believe only through this approach can the full diagnostic potential of CFD in rhinology be unlocked, while, to the best of our knowledge, existing applications of CFD have primarily focused on examining rather global parameters.

The Simulated Flow Field as a Diagnostic Interface

The simulated flow field within the nasal cavity quantitatively reflects the local distribution of one or more flow parameters, and visualization displays their correspondence with the anatomical structures. Of particular interest is the distribution pattern of WSS. This parameter describes the tangential forces on the nasal wall that are caused by adhesion of the passing air particles. WSS correlates with interactions between the flowing air and the mucous membrane in terms of mass and heat transfer as well as effects on both thermo- and mechanoreceptors. Consequently, the flow field—particularly the distribution pattern of WSS—may serve as a diagnostic interface for evaluating a patient's nasal breathing (►**Fig. 2**).[12,13]

However, this necessitates a point-to-point quantitative comparison with a valid reference for the flow field, for example, based on a sufficient statistical shape model (SSM).[14] The SSM needs to capture the broad natural variation in nasal cavity morphology, taking into account both the static geometry and the inner lining's fluctuations. It should encompass both healthy and symptomatic populations, representing individuals with either unimpaired or compromised nasal breathing, respectively.

Implementing the SSM would, within certain limits, enable the determination of whether a specific nasal cavity geometry facilitates normal airflow.[15] If this is confirmed but the patient still perceives nasal breathing problems, clinical investigation would be required to explore other potential causes, such as mucosal disease, inadequate structural support of the nasal sidewalls, or perceptual issues.

Discussion

Fluid–Structure Interaction

A central concern in rhinology is the nasal valve, which anatomically corresponds to the isthmus nasi.[16,17] According to Bernoulli's law, the dynamics of the nasal valve during inspiration are due to the changing relationship between the static pressure inside the nasal cavity and ambient pressure. The compliance of the nasal sidewalls is governed by these fluctuating pressure conditions, as well as by their intrinsic mechanical properties. During inspiration, the airflow acceleration in the nozzle-like constriction of the isthmus nasi leads to a locally enhanced difference between the decreasing intranasal static pressure and the constant ambient atmospheric pressure. Therefore, at the isthmus nasi, the inspiratory resulting inward-directed forces are particularly pronounced. Known as the Venturi effect, it can lead to a subsequently aggravated constriction of the isthmus area through the shifting nasal walls. Collectively, this is referred to as fluid–structure interaction (FSI).

Currently, addressing FSI in simulations of nasal breathing is challenging due to various technical complexities, most notably the difficulty in obtaining data on the mechanical properties of the nasal sidewalls. Disregarding FSI might generally be a minor issue, as exclusive nasal breathing usually occurs during resting respiration related to low flow rates,[18] which the boundary conditions involve. While at low flow rates the inward inspiratory shifting of the anterior nasal sidewalls is typically not significant, during intensified inspiration with elevated flow rates, bilateral inward shifting of the sidewalls serves as a physiological limiter of inflow, comparable to a Starling resistor. To a certain extent, this aligns with the intended functioning of the nasal valve.[19]

In contrast, asymmetrical nasal valve dynamics prove to be more critical and, therefore, require greater attention. Specifically, when one nostril collapses, while the other remains unaffected, questions arise about the sufficiency of the cartilaginous support on the affected side. Often, surgical enforcement is the first course of action, frequently without a comprehensive analysis of the underlying causes. Based on our experience, corroborated by the opinion of colleagues (Helmut Fischer via e-mail on April 24, 2021), asymmetrical nasal valve dynamics are more attributed to flow domain asymmetry than to unilateral instability of the nasal sidewall. Therefore, in most cases, correcting only the flow domain of the nose is already sufficient. Simulating the flow field under the assumption of rigid walls allows for isolating solely static geometry-related factors affecting nasal breathing from those concerning the condition of the nasal sidewall structure, the latter of which must be clinically assessed.

In closing, what appears as a limitation in current rhinologic CFD applications can conversely also offer advantages.

Nasal Airflow Misperception

The perception of airflow within the nasal cavity is most likely primarily facilitated by thermoreceptors, activated indirectly through the evaporative cooling of the mucous membrane during inhalation.[20] Mechanoreceptors, which directly respond to WSS, may also play a significant role.[21] Signals from these receptors are conveyed to the brain via the trigeminal system, creating the sensation of the intranasal airflow. This is influenced by both the airstream's distribution pattern and the allocation of receptors within the nose. Perception of nasal breathing as either impaired or normal is also subject to individual signal processing. In essence, the trigeminal system mediates the individual perception of the nasal cavity's patency.

In general, reliably distinguishing between objectively impaired nasal breathing and airflow misperception is a challenging task, often achievable only by the presence of unequivocal clinical findings. Due to their inherent limitations, conventional diagnostic methods like rhinomanometry merely offer marginal improvements to clinical evaluations. To accurately identify cases of nasal airflow misperception, it is crucial to verify whether the respective nasal cavity facilitates a normal airflow pattern. This confirmation might be attained through flow field simulation using CFD, complemented by comparison with a valid reference for quantitative analysis. In other words, the application of CFD could enable discrimination of objectively compromised airflow from solely misperceptions.

Fluctuations of the Flow Domain due to the Nasal Cycle

The nasal cycle is a physiological phenomenon in which the swelling state of the nasal mucosa periodically changes. Specifically, the inferior turbinates complementarily congest and decongest in an alternating pattern. Ideally, the overall patency of the nose remains largely unchanged during this process. The switching itself occurs relatively quickly compared with the periodicity of its occurrence.[22,23]

Due to the nasal cycle, diagnostic imaging may show a significantly changed flow domain in the same patient depending on the time of examination. Therefore, when applying CFD for the evaluation of nasal breathing, this temporal physiological variability in the nasal cavity's morphology should be taken into account by using a reference that represents these normal fluctuations. An SSM, as mentioned earlier, might be an appropriate means to address the issue.

Reduced Bias through Comparative Analysis

Assessing nasal breathing using CFD is very complex and inherently carries an elevated risk of error from multiple sources. These include technical aspects such as the choice of boundary conditions, computational grid meshing, and selection of a specific turbulence model, as well as investigator-related factors, particularly in image segmentation.

Employing an SSM to generate referential flow parameters for quantitative evaluation of the intranasal airstream simultaneously offers additional benefits by mitigating the aforementioned risks of bias. When a uniform methodology is applied to both the individual case under investigation and the SSM reference, errors are more likely to occur consistently. Consequently, these errors can be partially offset through comparative analysis.

Conclusion

Compared with conventional methods, CFD enables a fundamentally new approach for evaluating nasal breathing. To unlock the full diagnostic potential of this technology, new foundational considerations are instrumental, particularly regarding the essence of nasal breathing and how it can be adequately characterized. The intranasal flow field, specifically the distribution pattern of WSS, can serve as an interface reflecting the quality of nasal breathing in terms of bidirectional interactions between airflow and the mucous membrane. To quantitatively analyze this interaction for individual patients, reference parameters derived from an appropriate SSM are required. Implementing such an SSM is a challenge that we are currently working on.

A prerequisite for such nasal breathing assessment is imaging of the paranasal sinuses, including the nasal cavity, which is routinely performed to rule out mucosal disease in cases of impaired nasal breathing. The acquired two-dimensional image data not only provide morphological information but can also be subsequently used to assess respiratory intranasal airflow when needed. This possible dual use could facilitate the cost-effective implementation of CFD-based nasal breathing evaluation in clinical practice. While segmentation of the image data for reconstructing the 3D geometry of the nasal cavity is not yet fully automatable, artificial intelligence approaches might tackle this issue in the future.

Using CFD in conjunction with an SSM would enable the differentiation between normal and impaired nasal breathing and the precise localization of the problem, allowing for targeted surgical intervention when indicated. Thus, a possible paradigm shift in nasal breathing assessment may be on the horizon. An advanced model of the airflow-related intranasal physiology, which compliments the existing one and aligns well with the capabilities of the CFD methodology, could facilitate this development.[12,13]

Conflict of Interest
None declared.

Acknowledgments
We extend our gratitude to Mr. Jan Brüning (Charité – Universitätsmedizin Berlin, Biofluid Mechanics Laboratory) for his invaluable feedback on the manuscript and for his contributions to the subject matter, encompassing both computational and general fluid dynamics. He is also credited with the creation of ►**Fig. 1**.

Our thanks also go to Andreas Schulz (Graphic Design & 3D Animation, Berlin), who graciously designed ►**Figs. 2** and **3**.

References

1 Bermüller C, Kirsche H, Rettinger G, Riechelmann H. Diagnostic accuracy of peak nasal inspiratory flow and rhinomanometry in functional rhinosurgery. Laryngoscope 2008;118(04):605–610
2 Clement PA, Gordts FStandardisation Committee on Objective Assessment of the Nasal Airway, IRS, and ERS. Consensus report on acoustic rhinometry and rhinomanometry. Rhinology 2005;43 (03):169–179
3 Ta NH, Gao J, Philpott C. A systematic review to examine the relationship between objective and patient-reported outcome measures in sinonasal disorders: recommendations for use in research and clinical practice. Int Forum Allergy Rhinol 2021;11 (05):910–923
4 Mo S, Gupta SS, Stroud A, et al. Nasal peak inspiratory flow in healthy and obstructed patients: systematic review and meta-analysis. Laryngoscope 2021;131(02):260–267
5 Burgos MA, Sanmiguel-Rojas E, Del Pino C, Sevilla-García MA, Esteban-Ortega F. New CFD tools to evaluate nasal airflow. Eur Arch Otorhinolaryngol 2017;274(08):3121–3128
6 Flowgy. Accessed September 30, 2023 at: https://www.flowgy.com
7 Zachow S, Muigg P, Hildebrandt T, Doleisch H, Hege HC. Visual exploration of nasal airflow. IEEE Trans Vis Comput Graph 2009; 15(06):1407–1414
8 Quadrio M, Pipolo C, Corti S, et al. Effects of CT resolution and radiodensity threshold on the CFD evaluation of nasal airflow. Med Biol Eng Comput 2016;54(2–3):411–419
9 Hildebrandt T, Osman J, Goubergrits L. Numerical flow simulation: a new method for assessing nasal breathing. HNO 2016;64 (08):611–618
10 Hildebrandt T, Goubergrits L, Heppt WJ, Bessler S, Zachow S. Evaluation of the intranasal flow field through computational fluid dynamics. Facial Plast Surg 2013;29(02):93–98
11 Hildebrandt T. Principles of modern septoplasty. In: Behrbohm H, Tardy EM, eds. Essentials of Septorhinoplasty. 2nd ed. New York, NY: Thieme; 2016:122–127
12 Hildebrandt T, Heppt WJ, Kertzscher U, Goubergrits L. The concept of rhinorespiratory homeostasis: a new approach to nasal breathing. Facial Plast Surg 2013;29(02):85–92
13 Hildebrandt T. Das Konzept der Rhinorespiratorischen Homöostase—ein neuer theoretischer Ansatz für die Diskussion physiologischer und physikalischer Zusammenhänge bei der Nasenatmung [dissertation in German]. Freiburg im Breisgau, Germany: Albert-Ludwigs-Universität; 2011
14 Brüning J, Hildebrandt T, Heppt W, et al. Characterization of the airflow within an average geometry of the healthy human nasal cavity. Sci Rep 2020;10(01):3755
15 Hildebrandt T, Heppt W. A novel principle of nasal breathing assessment. 2023 Accessed September 23, 2023 at: https://figshare.com
16 Bruintjes TD, van Olphen AF, Hillen B, Huizing EH. A functional anatomic study of the relationship of the nasal cartilages and muscles to the nasal valve area. Laryngoscope 1998;108(07):1025–1032
17 Hildebrandt T, Brüning JJ, Schmidt NL, et al. The healthy nasal cavity-characteristics of morphology and related airflow based on a statistical shape model viewed from a surgeon's perspective. Facial Plast Surg 2019;35(01):9–13
18 Proctor DF. Form and function in the upper airways and larynx. In: Fishman AP, ed. The Handbook of Physiology. Section 3: The Respiratory System. Vol. 3: Mechanics of Breathing, Part 1. Bethesda, MD: The American Physiological Society; 1986:63–73
19 Bridger GP, Proctor DF. Maximum nasal inspiratory flow and nasal resistance. Ann Otol Rhinol Laryngol 1970;79(03):481–488
20 Zhao K, Jiang J, Blacker K, et al. Regional peak mucosal cooling predicts the perception of nasal patency. Laryngoscope 2014;124 (03):589–595
21 Elad D, Naftali S, Rosenfeld M, Wolf M. Physical stresses at the air-wall interface of the human nasal cavity during breathing. J Appl Physiol 2006;100(03):1003–1010
22 Eccles R. The central rhythm of the nasal cycle. Acta Otolaryngol 1978;86(5–6):464–468
23 Huizing EH, De Groot JAM. Functional Reconstructive Nasal Surgery. 1st ed. Stuttgart: Thieme; 2003:52

