Published in final edited form as:
Facial Plast Surg. 2010 August ; 26(4): 320–327. doi:10.1055/s-0030-1262314.

Objective Measures in Aesthetic and Functional Nasal Surgery – Perspectives on Nasal Form and Function

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Abstract

The outcomes of aesthetic and functional nasal surgery are difficult to assess objectively due to the intricate balance between nasal form and function. Despite historical emphasis on patient-reported subjective measures, objective measures are gaining importance in both research and the current outcomes-driven healthcare environment. Objective measures presently available have several shortcomings which limit their routine clinical use. In particular, the low correlation between objective and subjective measures poses a major challenge. However, advances in computer, imaging, and bioengineering technology are now setting the stage for the development of innovative objective assessment tools for nasal surgery that can potentially address some of the current limitations. Assessment of nasal form following aesthetic surgery is evolving from two-dimensional analysis to more sophisticated three-dimensional analysis. Similarly, assessment of nasal function is evolving with the introduction of computational fluid dynamics techniques, which allow for a detailed description of the biophysics of nasal airflow. In this paper, we present an overview of objective measures in both aesthetic and functional nasal surgery and discuss future trends and applications that have the potential to change the way we assess nasal form and function.

Keywords

Nasal surgery; outcomes; modeling; computational fluid dynamics; nasal valve; rhinoplasty; septoplasty; septorhinoplasty

INTRODUCTION

The outcomes of aesthetic and functional nasal surgery (e.g., septoplasty, rhinoplasty, nasal valve surgery, turbinoplasty, and septorhinoplasty) have been difficult to quantify objectively.[1] Traditional outcome measures have relied predominantly on patient-reported, quality-of-life and satisfaction, as these domains are felt to be the most important measures of success.2 However, while subjective measures are important to our understanding of outcomes in nasal surgery, the development of validated objective measures may allow us to quantify the effects of surgery, better understand the "why" behind subjective outcomes, and

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consequently suggest strategies to obtain better surgical outcomes. As nasal form and function are so closely intertwined, quantitative assessments can better define these relationships and how they are affected following nasal surgery. Objective measures can help us answers questions such as:

- Do specific surgical techniques actually achieve their intended purpose?
- To what degree should we alter the nasal soft tissues or nasal airway anatomy? How do these changes affect nasal function?
- How are nasal form and function interrelated? Can we predict how changes in nasal form will affect function?

This information can be applied to outcomes based research and allows for improved comparison of results across studies. Further development of these objective measures can potentially lead to the identification of clinical predictors for surgical success or the development of standard criteria for surgical decision support. Not only is this information useful within academia, but within commercial healthcare as well, given the mounting external pressure for quantifiable outcomes, particularly in the field of facial plastic surgery. Our field is increasingly being faced with challenges for insurance approvals and justification for performing procedures, and thus the need for objective data will only continue to grow.

Several characteristics of objective assessment techniques are important including ease of implementation, accuracy and reproducibility of results, standardization of technique, and availability and cost effectiveness of equipment.[3] Many of the currently available objective measures for aesthetic and functional nasal surgery are lacking in one or more of these characteristics, thus limiting their routine use in clinical and research arenas. Additionally, objective assessments often do not undergo rigorous tests of reliability and are open to interpretation in terms of universal acceptance and availability.[4] However, advances in computer, imaging, and bioengineering technology are now setting the stage for the development of innovative objective assessment tools for nasal surgery that can potentially address some of the current limitations. In this paper, we present an overview of objective measures in both aesthetic and functional nasal surgery and discuss future trends and applications that have the potential to change the way we assess nasal form and function.

OBJECTIVE ASSESSMENT OF NASAL FORM

Within the realm of aesthetic nasal surgery, objective assessment methods have historically been based on two-dimensional (2D) facial analysis with techniques such as cephalometry, anthropometry, or photogrammetry.[5] Cephalometric radiographs of the head are obtained in a standardized manner where the X-ray source is in a fixed relationship with the subject. A variety of bony landmarks and planes can be used for analysis on the plain radiograph. Cephalometric analysis has been applied to the nose for determining changes in nasal tip projection and rotation following septorhinoplasty.6 Werther and colleagues utilized the nasion, articulare, and pogonion as cephalometric reference points as they were easily identifiable bony landmarks. Although commonly used by oral and maxillofacial surgeons, cephalometric analysis has not been widely adopted in aesthetic facial surgery as it does not allow for detailed soft tissue analysis.

While cephalometry utilizes bony landmarks to generate measurements on plain radiographs, anthropometry refers to the measurement of specific surface anatomy characteristics or landmarks either directly (on the patient) or indirectly (on photographs). Traditional anthropometry is based on the direct measurement of numerous facial landmarks using a caliper or other measuring device and is encumbered by the amount of time involved, both for the patient and assessor. Direct anthropometric measurements have been used to assess the change in nasal tip projection following rhinoplasty and to determine nasal length, tip projection, and radix projection.[7, 8]

Modern day anthropometry has abandoned cumbersome direct measurements and has now been supplanted by photogrammetry, an indirect form of anthropometry that has been in use for over 40 years. Photographs are ideal instruments for facial analysis as they can be obtained relatively quickly and serve as a permanent record.[5] However, the fact that a photograph is a 2D representation of a three-dimensional (3D) structure can pose potential limitations for analysis. Additionally, measurements from photographs can be affected by changes in lighting and lens distortion. Despite these limitations, with advances in digital photography and imaging, photogrammetry has become a somewhat ubiquitous method for facial analysis and evaluation of various anatomic parameters in aesthetic nasal surgery. Digital photographs have become a key component of the pre- and post-operative patient assessment, and the use of imaging software has greatly simplified and streamlined measurement of anthropometric features on digitized images.

Common post-operative outcomes measured using photographic analysis have been nasal tip projection, nasal tip rotation, and nasolabial angle.[9, 10] Spörri and colleagues developed an objective computer-assisted technique to assess nasal tip projection and nasolabial angle.[10] They noted interinvestigator variability of less than 10% and found that the objective measurements correlated well with the subjective assessment of the surgeon. Ingels and Orhan measured nasal projection using the Goode method and nasolabial angle on digitized photographs using Adobe Photoshop.[9] Park and collaborators developed a computerized system of photogrammetric profile analysis to help identify specific facial problems and provide surgeons with analytic information that would aid in surgical planning.[11] Several other studies have utilized similar photographic facial analysis and anthropometric measurements to quantify facial form and post-surgical changes.[12-14]

While the use of digital photography and imaging has become commonplace in facial plastic surgery, the fundamental challenge is that this medium continues to represent the 3D structure of the face in a 2D format. Differences in facial depth and shape are simply not accounted for by 2D analysis.[15] This limitation has led to the adoption of a variety of techniques to acquire data and perform facial analysis in three-dimensions including stereophotogrammetry, computed tomography (CT), and laser surface scanning. These tools can be used to make accurate surface measurements, assess volumetric changes, and evaluate facial shape, texture, and skin tone in 3D.[16]

Three-dimensional imaging within the field of medicine began with stereophotogrammetry – a technique that was first reported in 1967 and utilizes multiple cameras at different locations to triangulate the shape of an object.[17] Stereophotogrammetry has been used to study the growth and development of the nose as well as to quantify changes in the nose following rhinoplasty.[18, 19] Various commercial products using principles of stereophotogrammetry have been developed to generate 3D images and are currently available for purchase and clinical use.

Developments in computed tomography technology and processing now allow for relatively quick generation of 3D image reconstructions from sequential axial images using a surface rendering technique. Disadvantages of CT imaging include radiation exposure to the patient as well as the potential for image artifacts caused by metal objects in the oral cavity.[16] Three-dimensional CT imaging has not gained widespread use for purposes of aesthetic nasal analysis.

Another increasingly popular tool with potential for applications in aesthetic nasal surgery is 3D laser surface scanning technology. Similar to the triangulation based techniques in stereophotogrammetry, laser surface scanning utilizes a laser light stripe projected onto an object and generates a 3D image based on measurements of distortion in the light viewed from an offset camera.[16] Although this method can only evaluate visible surfaces, it is non-invasive, fast, and allows for full 3D soft tissue analysis.[15] Chau and colleagues recently demonstrated the use of laser surface scanning to objectively quantify and analyze aesthetic changes in the nose following septorhinoplasty. They also suggest that similar objective evaluation may be useful to assess aesthetic changes in the nose associated with non-aesthetic nasal procedures such as septoplasty.[20] At this time, one of the biggest barriers to adoption of these 3D imaging systems is the associated cost. However, as computer and imaging technology advances, we can expect to see continued innovation in 3D medical imaging and the development of more affordable systems for mainstream clinical use.

OBJECTIVE ASSESSMENT OF NASAL FUNCTION

A variety of objective, functional outcome measures are available for the assessment of patients with nasal airway obstruction. The assessment of nasal airway patency dates back to the turn of the century with rudimentary methods based on the principle of water vapor condensation on a mirror or plate held in front of the nose.[21] Since that time, more sophisticated functional measures have been developed including rhinomanometry, acoustic rhinometry (AR), and peak nasal inspiratory flow (PNIF).

Rhinomanometry is a technique used to determine nasal airway resistance by measuring transnasal pressure drop and airflow simultaneously. Active anterior rhinomanometry is the preferred technique, where the patient actively breathes through one nostril while pressure is monitored in the contralateral nostril. In contrast, passive rhinomanometry, where airflow is controlled by a mouthpiece, has been shown to be less accurate. Also, posterior rhinomanometry is difficult because many patients have gag reflexes when the pressure sensor is inserted in the nasopharynx.[22] Rhinomanometry has been used to investigate changes in nasal resistance following topical decongestion [23], nasal valve surgery [24], and septoplasty.[25] Weaknesses of rhinomanometry include the inability to detect the location of obstruction and the requirement of a well-trained operator.[26]

Since its introduction in 1989,21 acoustic rhinometry (AR) has been employed in a multitude of scientific investigations to study nasal physiology and to document surgical and pharmacological interventions.[27] Because AR is easy, quick, non-invasive, and relatively inexpensive, it is a very attractive tool and one of the most common objective techniques used to investigate nasal patency. AR provides an estimate of the cross-sectional area (CSA) of the nasal passages as a function of distance from the nostrils.21 The technique is based on the generation of sound waves and detection of reflected waves, with a mathematical algorithm being used to translate changes in sound impedance into changes in cross-sectional areas. Accurate measurements require a quiet room, a well-trained operator, controlled air temperature and air humidity, a good sealing between the nostrils and the AR tube, and no deformation of the external nose.22 Normative values have been published for healthy adults of different races,28 and AR has been used in a variety of clinical applications including assessing changes in nasal CSA following rhinoplasty,29 documenting dynamic changes in nasal airway patency related to nasal valve collapse,[30] and for investigating the nasal cycle.[31] However, an understanding of the limitations of AR is essential for proper interpretation of data collected with the technique. One feature intrinsic to AR is that CSA measurements are accurate only in the anterior nose, with measurements beyond 5 cm from the nostrils being overestimated by AR compared to measurements derived from CT scans from the same patient.[32] Another known limitation of AR is that it overestimates cross-sectional areas after constrictions that are very narrow or after abrupt changes in nasal geometry.[33]

Peak nasal inspiratory flow (PNIF) is a measure of the highest flow a patient can achieve during maximum forced nasal inspiration through both nostrils. PNIF is a simple, inexpensive, and fast technique. In a study of 40 healthy volunteers and 53 patients with symptomatic nasal obstruction, Bermüller and collaborators found that a cutoff of 120 L/min distinguished patients from controls with a sensitivity of 66% and a specificity of 80%.34 Similar results were reported by Starling-Schwanz and coworkers.35 However, a major weakness of PNIF is that it is effort-dependent. Accurate measurements depend on optimal patient cooperation, correct instructions from the investigator, and standardized techniques. Additionally, PNIF reflects not only nasal patency, but also lung health because it is correlated to lung ventilation parameters, such as forced vital capacity (FVC) and forced expiratory volume in 1 second (FEV_1).[35] Finally, the greater importance of nasal tissue compliance during peak airflow may explain why some authors found no correlation between PNIF and acoustic rhinometry or rhinomanometry, which are usually performed at lower nasal airflows.[34]

Several other tools have been developed to objectively assess nasal airflow but have not gained widespread adoption for routine clinical use. Hanif and Eccles first reported the use of nasal spirometry in 2001, by using a portable spirometer fitted with a nasal adapter to measure expired volume from each nostril and calculating a nasal partitioning ratio (NPR) to determine relative dominance of one side.36 They subsequently utilized nasal spirometry to assess the severity of nasal septal deviation before and after septoplasty.37 Unlike rhinomanometry, nasal spirometry can be used in patients with complete unilateral nasal obstruction. Another tool is Odiosoft Rhino (OR), a non-invasive measure which utilizes the sound of nasal airflow to objectively assess nasal obstruction.38 Nasal airway sounds are recorded using a small microphone placed just inside the nostril and the OR software calculates sound intensity, which is hypothesized to correlate to nasal diameter and nasal patency. Compared to rhinomanometry, the OR method is noninvasive, relatively easy to perform, inexpensive, and does not require significant patient cooperation.38

All objective tests currently available to assess nasal airflow share a common weakness: a poor correlation with patient symptom scores. In general, objective measures correlate with patient symptoms fairly well at the population level, but correlations at the individual level are low.[26] A similar phenomenon is sometimes observed when different types of objective measures are compared, namely statistical significance at the population level, but low correlation coefficients. For example, Kjaergaard and collaborators found that patients with larger PNIF had wider nasal cavities when assessed by AR, but the correlation coefficient between PNIF and cross-sectional area was small.[39] These poor correlations may reflect large experimental error in objective measures or a true poor correlation among objective measures as well as between objective and subjective measures. Due to these inconsistencies, current objective measures cannot currently be used to predict successful outcomes after surgical or pharmacological therapy.[26]

OBJECTIVE ASSESSMENT OF NASAL FORM AND FUNCTION

The need for better information at the individual level has encouraged the development of three-dimensional computational fluid dynamics (CFD) models of airflow in the nasal passages. CFD is the study of numerical solutions of the equations that govern airflow, called the Navier-Stokes equations, which are derived from Newton's Law of Conservation of Momentum. In general, given a tube of any shape and the physical conditions producing airflow through the tube (called boundary conditions), the Navier-Stokes equations can be solved to obtain information about the flow such as velocity, pressure exerted by the fluid on the tube walls, allocation of the flow to different regions within the tube, how much the flow swirls (vorticity), and turbulence.[40]

CFD models of the nasal airways utilize 3D reconstructions generated from CT or magnetic resonance imaging (MRI) data, and can provide highly detailed information about anatomical structure and airflow behavior (Fig. 1). When coupled with transport equations for inhaled or sprayed material or heat and water vapor exchange, similarly detailed information on potential toxicants, drug delivery, and air conditioning in the nose can be obtained.

Early three-dimensional CFD models of the human nasal passages were reported in the literature in the mid-1990s.[41, 42] Since then, many groups have created similar models from simplified geometries as well as individual CT scans and used them to estimate airflow patterns and other flow variables such as pressure distribution, velocity profiles, flow allocation, nasal resistance, wall shear forces, vorticity, and turbulence location and intensity. Such models have been used to describe the effects on nasal airflow patterns of several pathologies, including sleep apnea,[43] atrophic rhinitis,[44] sinus disease,[45, 46] septal deviation,[47] and hypertrophic turbinates,[48] both in actual patients and in normal geometries digitally modified to mimic pathological noses. Models have also been used to describe the impact on nasal airflow following turbinate reduction,[49] septoplasty,[49] implants,[44] and sinus surgery,[50, 51] again in both actual patients and by modifying normal geometry. A small number of studies have investigated airflow in the same patient before and after actual surgery,[44, 52] and a few studies have tried to address the effects of inter-individual variability in nasal anatomy.[53, 54] Most of these CFD studies reported no clinical data and were limited to descriptions of nasal airflow biophysics, such as flow patterns and pressure distribution. Therefore, the connection between biophysical parameters and patient symptoms remains largely unknown. So far, only a few studies have attempted to suggest physical parameters that may correlate to clinical findings, including nasal mucosal surface area and mucus dehydration in atrophic rhinitis[44] and wall shear stress impact on nasal sensation of airflow and septal perforations.[55, 56]

More recently, Garcia and collaborators digitally modified the nasal geometry of a normal nose to create septal deviations in nine locations (anterior, middle, posterior vs. inferior, middle superior).[57] The computer-derived nasal resistance was much higher when the deviation was located in the nasal valve, while posterior septal deviations had little effect on nasal resistance. These observations are supported by rhinomanometry measurements performed by Cole and collaborators, who inserted fiberfoam slabs in various locations of the nasal passages and observed that nasal resistance is much more affected by anterior than posterior septal deviations.58 These findings are in agreement with the observation that patients with anterior septal deviations are more likely to benefit from septoplasty than patients with posterior deviations.59 Thus this study helps link CFD-derived nasal resistance with clinical interpretations of nasal resistance.57

The primary factor that has hindered correlation studies between CFD-derived physical parameters and clinical findings is the labor-intensive nature of building such computational models. Thus previous studies used very small cohorts (five patients or less) with a focus more on feasibility than clinical correlation. Many of these studies also did not have corroborating post-surgical data for comparisons. While a few CFD-derived variables have been suggested that could predict state of health, more studies are needed to establish these or other variables as reliable predictors of a patient's symptoms. Variables are needed that can discriminate between symptomatic and healthy cases. If correlations between physical parameters and patient's symptoms can be demonstrated, CFD may become a useful tool to predict surgical outcome. For example, in a case where it is unclear whether turbinate reduction or septoplasty is the best option, virtual manipulation of nasal geometry followed by CFD analysis may reveal which surgical procedure would be the most beneficial for that patient.

The availability of both fast computers and computational modeling software has made the process of creating a nasal CFD model relatively straightforward. A significant body of literature now exists that can provide guidance on running nasal airflow simulations and calculating CFD-derived variables. Some software programs can also be used to digitally alter the shape of an existing nasal geometry, thus enabling virtual surgery.[57] In addition, the large number of CFD studies that have been done to date in non-pathological airways provides a good start for establishing normative values of many CFD-derived variables.

It is important to acknowledge that current CFD technology has some significant limitations. First, although it is possible to build models from MRI scans, the best models are currently built from CT scans due to their better resolution, thus subjecting patients to radiation. Second, many current models make several approximations (laminar flow, rigid walls, steady-state flow) that are reasonable in many cases, but do not always hold. More studies are needed to assess the effects of tissue compliance, turbulence, and time-dependent phenomena. Third, the cost and time to build CFD models are still high as compared to other objective measures such as acoustic rhinometry. However, both the cost and the time to build CFD models have fallen significantly in the last decade, a trend that is expected to continue in the years to come. Finally, like other objective measures, CFD models are based on an individual set of images and thus are a snapshot of nasal structure at the time of imaging. To extrapolate results to other nasal mucosa states, more detailed studies will be necessary. Because of limitations such as these, CFD technology is still emerging as a tool to assess nasal physiology. More studies, in particular experimental validation, are needed to demonstrate the correlations between CFD-derived physical parameters and clinical data.

SUMMARY

Without a doubt, the current state of objective assessment in aesthetic and functional nasal surgery is in rapid evolution, fueled largely by advances and innovation in computing and imaging technology. The importance of tools to objectively analyze our surgical interventions will have increasing day-to-day clinical importance in our current outcomes-driven healthcare environment and in the research arena.

Within the aesthetic realm, patient satisfaction will continue to remain one of the most important outcomes and measures of success. However, the continued development of objective assessment tools will allow for quantitative, detailed analysis of nasal form and provide a means for quantifying facial anthropometric measurements and changes. This anthropometric data can be used to help define objective aesthetic ideals by correlating this information with patient-reported or observer-based measures. Digital imaging and computing technology has begun to transform facial analysis from a more primitive two-dimensional context to more sophisticated analysis in three-dimensions. Hardware and software packages are already commercially available and this technology will likely see greater adoption and use as it becomes more affordable and accessible for routine clinical use. Ultimately, the information gained from these systems could be used to develop clinical predictors or for pre-intervention modeling and surgical decision making based on pre-defined aesthetic ideals.[4]

The evolution of nasal airflow modeling is expected to provide surgeons with objective criteria that will help evaluate the success of nasal surgery. In addition, other applications of CFD technology are expected, such as drug delivery optimization, airflow considerations during healing, and the development of software tools that allow surgical approaches to be tested in a virtual environment before being implemented. New structural data beyond CT and MRI imaging, such as epithelial types, nerve locations, and airway wall compliance will drive CFD models to integrate micro- and macro-anatomy, airflow patterns, pressure, and other flow variables. Modeling capabilities beyond CFD itself, such as coupling fluid-structure interaction with CFD, will push the development of hybrid models that can help surgeons better understand conditions like sleep apnea and upper airway collapse.

With the current trend toward increasing communication and collaboration between surgeons and computational modelers, the future utility of computational modeling in surgical decision-making is well worth looking forward to. Ultimately, the development of sophisticated computing and bioengineering tools that integrate patient-reported outcome measures with objective data will certainly bring a new dimension to the analysis of nasal form and function in aesthetic and functional nasal surgery.

Acknowledgments

This manuscript was funded in part by grant 1R01EB009557-01 from the National Institutes of Health/National Institute of Biomedical Imaging and Bioengineering.

Funding/Support: This manuscript was funded in part by grant 1R01EB009557-01 from the National Institutes of Health/National Institute of Biomedical Imaging and Bioengineering.

Abbreviations Used

AR	acoustic rhinometry
PNIF	peak nasal inspiratory flow
CFD	computational fluid dynamics
CT	computed tomography
MRI	magnetic resonance imaging
CSA	cross-sectional area
NPR	nasal partitioning ratio
2D	two-dimensional
3D	three-dimensional
OR	Odiosoft-Rhino

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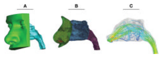

Figure 1.

(A) A 3D reconstruction of the external nose and nasal passages (paranasal sinuses excluded) of a patient with atrophic rhinitis. (B) A computational mesh of the same structure. (C) Streamlines of inspiratory airflow simulated using computational fluid dynamics.