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Changes in nasal airflow and heat transfer correlate with symptom improvement after surgery for nasal obstruction

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ABSTRACT

Surgeries to correct nasal airway obstruction (NAO) often have less than desirable outcomes, partly due to the absence of an objective tool to select the most appropriate surgical approach for each patient. Computational fluid dynamics (CFD) models can be used to investigate nasal airflow, but variables need to be identified that can detect surgical changes and correlate with patient symptoms. CFD models were constructed from pre- and post-surgery computed tomography scans for 10 NAO patients showing no evidence of nasal cycling. Steady-state inspiratory airflow, nasal resistance, wall shear stress, and heat flux were computed for the main nasal cavity from nostrils to posterior nasal septum both bilaterally and unilaterally. Paired *t*-tests indicated that all CFD variables were significantly changed by surgery when calculated on the most obstructed side, and that airflow, nasal resistance, and heat flux were significantly changed bilaterally as well. Moderate linear correlations with patient-reported symptoms were found for airflow, heat flux, unilateral allocation of airflow, and unilateral nasal resistance as a fraction of bilateral nasal resistance when calculated on the most obstructed nasal side, suggesting that these variables may be useful for evaluating the efficacy of nasal surgery objectively. Similarity in the strengths of these correlations suggests that patient-reported symptoms may represent a constellation of effects and that these variables should be tracked concurrently during future virtual surgery planning.
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1. Introduction

Nasal airway obstruction (NAO) is a common affliction (Jessen and Malm, 1997). Surgeries to correct anatomic deformities contributing to NAO are often successful, but many such procedures have less desirable outcomes (Andre et al., 2006; Dinis and Haider, 2002; Illum, 1997; Singh et al., 2006). Studies investigating non-desirable outcomes have noted a lack of clinical tools providing consistent, objective measures of nasal physiology. In addition, difficulties correlating measurements with patient-reported symptoms indicate that new tools and measures are needed (Kjaergaard et al., 2008; Lam et al., 2006; Pawar et al., 2010; Rhee, 2009; Schumacher, 2002).

Computational fluid dynamics (CFD) is a tool that can fill this need. CFD modeling of nasal physiology has evolved from two-dimensional airflow simulations in simplified channels (Tarabichi and Fanous, 1993) to three-dimensional models of airflow, heat, water vapor, and inhaled material transport in anatomically-accurate reconstructions of the nasal passages based on medical images (Chen et al., 2009; Frank et al., 2013; Garcia et al., 2007; Kimbell et al., 2007; Lindemann et al., 2006; Rhee et al., 2012; Subramaniam et al., 1998; Wexler et al., 2005). Nasal CFD models can estimate many physiologically relevant variables in exquisite anatomical detail, and are the focus of an increasing number of studies (Leong et al., 2010; Wang et al., 2012).

For CFD to be useful to nasal surgeons, variables must be identified that reflect surgical changes and correlate with symptoms, e.g., feelings of congestion, blockage, breathing difficulties, sleep disturbance, and air hunger (Rhee and McMullin, 2008). Nasal resistance is affected by reduction in airway cross-sectional area and may relate to congestion and blockage. Abnormal patterns of airflow may disrupt normal sensation stimuli (Garcia et al., 2007) so that airflow and wall shear stress may relate to congestion, breathing difficulties, air hunger, irritation, and pain that disturbs sleep. The nose is a finely-tuned heat regulator and contains densely distributed thermoreceptors in the nasal vestibule (Jones et al., 1989). Disruption of these systems may lead to extreme mucosal drying and/or cooling with compensatory excesses in blood flow and mucus production, or lack of airflow sensation with increased feelings of congestion. Such disruptions can be inferred from CFD simulations.

CFD models have been used to estimate surgical effects on some of these variables but studies are lacking that test the discriminatory capability of these variables with respect to surgery, or relate

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these variables to patient symptoms. As part of a prospective study designed to fill these gaps, we developed methods to compare CFD-derived nasal resistance (CFD-NR) with validated patient-reported measures of NAO symptoms before and after surgery. In a preliminary application of these methods to two NAO patients, no relationship was evident between bilateral CFD-NR and symptom severity but a positive trend emerged when bilateral CFD-NR was replaced with unilateral CFD-NR on the most obstructed nasal side (Kimbell et al., 2012).

The goals of the present study were to expand these results to a larger cohort of NAO patients and compute airflow, wall shear stress, and heat flux in addition to CFD-NR pre- and post-surgery. The results were used to test the hypotheses that these variables can (1) discriminate between pre-surgery and post-surgery states, and (2) correlate with scores from symptom surveys administered before and after surgery.

2. Methods

2.1. Patient reported measures

The patient-reported measures of NAO symptoms used here were the Nasal Obstruction Symptom Evaluation (NOSE) scale to assess general symptomology and quality of life, and a 0-to-10 visual analog scale (VAS) for unilateral airflow sensation. The NOSE scale has been validated for NAO symptoms (Stewart et al., 2004a, 2004b) and consists of patient ratings, over the past month, of feelings of (1) nasal congestion or stuffiness, (2) nasal blockage or obstruction, (3) trouble breathing through the nose, (4) trouble sleeping, and (5) ability to get enough air through the nose during exercise or exertion. Patients are asked to use a 0-to-4 scale with 0=Not a problem, 1=Very mild problem, 2=Moderate problem, 3=Fairly bad problem, and 4=Severe problem. Each score is multiplied by 5 and the five scores are added together, producing total scores of 0 and 100 for the best and worst cases, respectively. For the VAS scale, patients rated sensation of airflow on each side of their nose separately from 0=completely blocked to 10=completely open.

2.2. Patients and treatment

NAO patients who were at least 15 years old, had a clinical diagnosis of non-reversible, surgically treatable nasal obstruction (deviated septum, turbinate hypertrophy resistant to medical treatment, or lateral nasal wall collapse), elected to have surgery, and provided informed consent were recruited from the Ear, Nose, and Throat clinic at Medical College of Wisconsin (MCW) (Kimbell et al., 2012). This study was approved by the Institutional Review Board at MCW and written informed consent was obtained from all subjects. Axial computed tomography (CT) scans with pixel sizes of 0.303 or 0.313 mm and 0.6-mm thickness were obtained pre-operatively and 5 to 8 months post-operatively in 24 subjects. After exclusions for functional endoscopic sinus surgery and unrepaired anatomical defects, pre- and post-surgery CT scans were available for 19 subjects.

To minimize nasal cycling effects on CFD results, only subjects in whom mucosal thickness was generally symmetrical in right and left sides in both pre- and post-surgery scans were included in this analysis. This group consisted of 10

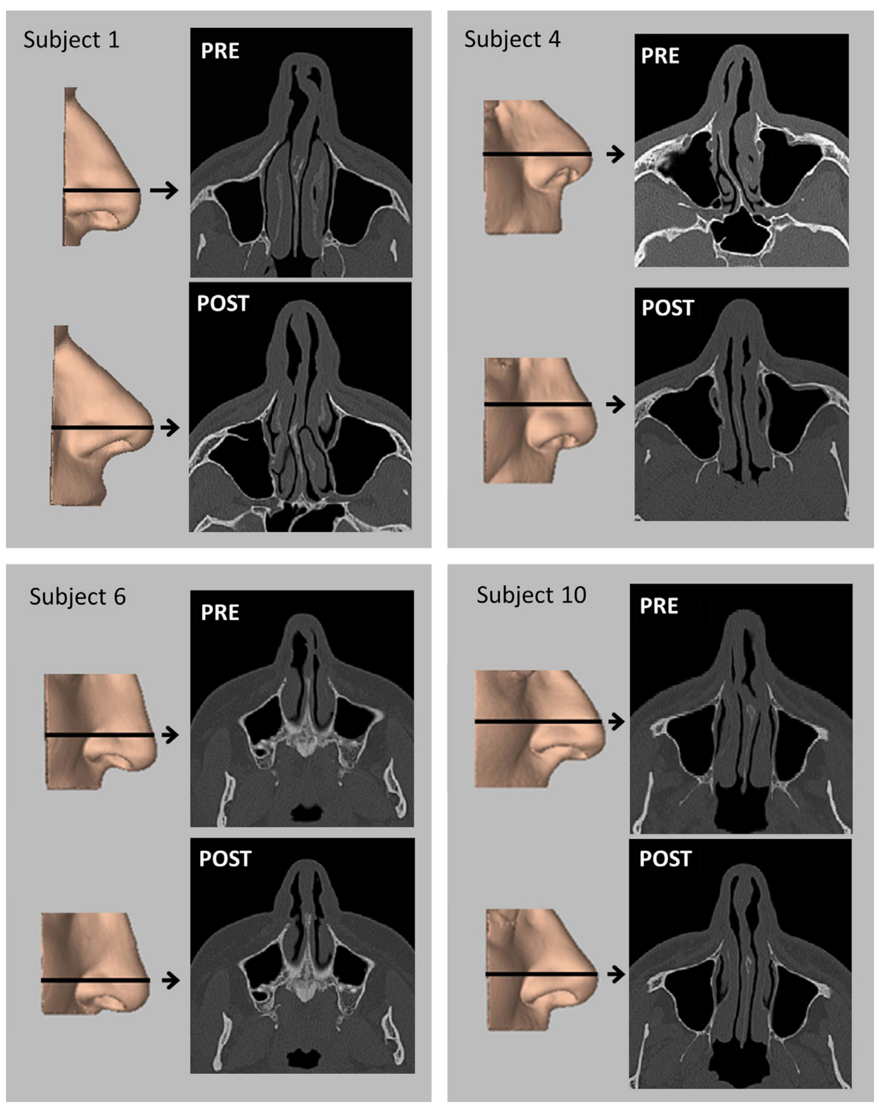

Fig. 1. Three-dimensional reconstructions of the external nose before (PRE) and after (POST) surgery for nasal airway obstruction in four subjects, with axial images from pre- and post-surgery CT scans. Arrows indicate level of scan image.

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