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Estimates of nasal airflow at the nasal cycle mid-point improve the correlation between objective and subjective measures of nasal patency

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ABSTRACT

Introduction: The nasal cycle represents a significant challenge when comparing pre- and post-surgery objective measures of nasal airflow.
Methods: Computational fluid dynamics (CFD) simulations of nasal airflow were conducted in 12 nasal airway obstruction patients showing significant nasal cycling between pre- and post-surgery computed tomography scans. To correct for the nasal cycle, mid-cycle models were created virtually. Subjective scores of nasal patency were obtained via the Nasal Obstruction Symptom Evaluation (NOSE) and unilateral visual analog scale (VAS).
Results: The correlation between objective and subjective measures of nasal patency increased after correcting for the nasal cycle. In contrast to biophysical variables in individual patients, cohort averages were not significantly affected by the nasal cycle correction.
Conclusions: The ability to correct for the confounding effect of the nasal cycle is a key element that future virtual surgery planning software for nasal airway obstruction will need to account for when using anatomic models based on single instantaneous imaging.

1. Introduction

There is much interest in the development of a virtual surgery tool to optimize the outcomes of nasal airway obstruction (NAO) surgery. Currently, surgical planning for NAO patients relies on subjective symptoms, physical exam findings, and physician judgment without any objective measurements. In theory, a virtual surgery software tool based on computational fluid dynamics (CFD) simulations of nasal airflow can be developed to identify which patients would benefit the most from surgery and to select the optimal surgical procedure for each patient (Hariri et al., 2015; Rhee et al., 2011). This virtual surgery tool will most likely rely on instantaneous imaging (computed tomography scans or magnetic resonance imaging) to capture an individual's nasal anatomy. Therefore, a key challenge for future virtual surgery tools is the need to account for the spontaneous fluctuation in nasal mucosa engorgement known as the "nasal cycle" (Eccles, 2000; Patel et al., 2015; Quine et al., 1999).

In the classical nasal cycle, unilateral airflow switches between the left and right nostrils every 2–3 h in the absence of any external stimuli, while bilateral airflow remains approximately constant (Eccles, 2000; Hasegawa and Kern, 1978). However, some patients exhibit different patterns of spontaneous fluctuations, including non-reciprocal and/or non-cyclical airflow fluctuations (Flanagan and Eccles, 1997). For this reason, a single snapshot of a patient's nasal passage does not always reflect the average airflow the patient experiences during her/his daily activities. Our group recently reported a methodology to simulate the nasal cycle and quantify flow variables at the mid-cycle point (Patel et al., 2015). The method requires the creation of multiple nasal cycle models for each surgical state (i.e., pre-surgery and post-surgery), running CFD simulations in each model, and fitting a curve to describe the relationship between flow variables and inferior turbinate thickness so that flow variables can be estimated at the mid-cycle. This method was previously applied to simulate the nasal cycle in two NAO patients and the results revealed that the nasal cycle can dramatically influence objective measures of surgical outcomes (Garcia et al., 2015a; Patel et al., 2015).

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The nasal cycle needs to be accounted for when quantifying changes in objective measures after NAO surgery. The method described in our previous study (Patel et al., 2015) was very labor-intensive due to the requirement to create multiple models for each surgical state, which prevented the analysis of a larger sample size. In the present paper, we describe an alternative strategy that requires the creation of a single pre-surgery mid-cycle model and a single post-surgery mid-cycle model. This new method is much faster to perform, but it was unclear whether the two methods would provide equivalent results. Here, we demonstrate that the two methods provide similar results, which allowed us to investigate a larger cohort of 12 cycling NAO patients. Our results reveal that the correlation between airflow variables and subjective nasal patency is higher after correcting for the nasal cycle.

2. Methods

2.1. Patient selection

This project was approved by the Medical College of Wisconsin's IRB committee and each patient gave informed consent. This manuscript is part of a larger study investigating the correlation between subjective and objective measures of nasal airflow (Dayal et al., 2016; Frank-Ito et al., 2014; Garcia et al., 2016; Hariri et al., 2015; Kimbell et al., 2013; Patel et al., 2015; Rhee et al., 2014; Sullivan et al., 2014). The cohort consisted of 27 patients all undergoing surgery to treat chronic nasal airway obstruction (septoplasty, turbinectomy, and/or functional rhinoplasty). For each patient, a single set of pre- and post-operative CT scans were obtained with 0.6 mm increments and in-plane resolution of 0.31 mm.

Patients exhibiting significant nasal cycle between pre- and post-surgery scans were selected based on changes in mucosal engorgement, as follows. A relative distance along the nasal cavity was defined as $D = z/L_{septum}$, where z is the distance from the nostrils and L_{septum} is the septum length from nostrils to nasal choana (Fig. 1). The cross-sectional area (CSA) of the inferior turbinate was averaged over five uniformly-spaced coronal sections located at distances $0.5 \leq D \leq 0.9$ (Fig. 2). (Sections in the anterior nose were not used because several patients underwent turbinate reduction that was limited to the anterior nose.) The percentage change in CSA between pre- and post-surgery scans was defined as $Percent\ \ Change = 100 \times |CSA_{POST} - CSA_{PRE}|/CSA_{PRE}$ for each nasal cavity in each patient. Patients with percent changes in mucosal engorgement greater than 15% were defined to have significant nasal cycle differences between the pre- and post-surgery scans. Based on this criterion, 12 out of the 27 patients were identified as requiring a nasal cycle correction.

2.2. Subjective scores of nasal patency

Patients were administered the Nasal Obstruction Symptom Evaluation (NOSE) to collect information on subjective symptoms before and after surgery (Stewart et al., 2004a). The NOSE scale is a disease-specific quality-of-life instrument for NAO that has been validated for septoplasty and nasal valve repair, and is used to measure surgical success (Rhee et al., 2014; Stewart et al., 2004b; Stewart et al., 2004a). The NOSE scale was selected because (a) it is simple and quick, (b) it is the quality-of-life (QOL) instrument most frequently used to assess surgical outcomes in NAO, and (c) it is more specific for NAO than other rhinological QOL instruments (Hopkins, 2009). It is a five item scale where each patient scores, over the past month, their symptoms of nasal congestion, nasal blockage, trouble breathing through the nose, trouble sleeping, and air hunger sensation using a scale from 0 (not a problem) to 4 (severe problem). These numbers are summed and multiplied by 5 to give a score that ranges from 0 (no symptoms) to 100 (severe symptoms).

Unilateral visual analog scale (VAS) scores for nasal airflow were also collected before and after surgery. Patients were asked to cover one nostril and rate their ability to breathe through the uncovered nostril on a scale of 1 (completely obstructed) to 10 (no obstruction). The VAS score was a subjective measure of instantaneous airflow at the time of consultation, while the NOSE score was used to assess the symptoms of nasal obstruction during the past month. For each patient, either the left cavity or the right cavity was assigned as the most obstructed side based on the pre-surgery VAS scores.

2.3. Creation of pre- and post-surgical models

Three-dimensional (3D) models of the pre-surgery and post-surgery nasal anatomy were created for each patient in Mimics^{TM} 16.0 (Materialise Inc., Leuven, Belgium) based on the CT scans. The nasal passage extended from the nostrils to the nasopharynx while excluding the paranasal sinuses. Consistent borders along the sinus ostia between pre- and post-surgical models were obtained by co-registering the models based on facial bones.

2.4. Creation of nasal cycle models

Nasal cycle models were created for both surgical states (i.e., pre-surgery and post-surgery) using the Morphology Operations tool in Mimics^{TM} (Fig. 3). This tool allows users to erode or dilate masks by an integer number of pixels. Using this tool, the airspace around the inferior and middle turbinates was reduced/expanded to reproduce the effect of mucosal congestion/decongestion (Fig. 3). When creating the pre-surgery batch of nasal cycle models, the post-surgery anatomy was used as a limit, so that the nasal cycle models stayed within the range of mucosal congestion/decongestion depicted in the CT scans. In other words, it was assumed that the pre- and post-surgery CT scans depicted the extremes of mucosal congestion/decongestion in each patient. Similarly, when creating the post-surgery batch of nasal cycle models, the pre-surgery anatomy was used as a limit to morphological changes of the airspace surrounding the inferior and middle turbinates.

2.5. Computational fluid dynamics (CFD) simulations

Biophysical measures of nasal airflow were quantified using computational fluid dynamics (CFD) using methods previously described (Garcia et al., 2007; Kimbell et al., 2013; Sullivan et al., 2014). Briefly, the nasal models were meshed with approximately 4 million tetrahedral cells in ICEM-CFD 14.0 (ANSYS, Inc, Canonsburg, Pennsylvania). The steady-state Navier-Stokes equations were solved in Fluent 14.0 (ANSYS, Inc) assuming laminar flow. The following boundary conditions were used: (1) gauge pressure at the inlet (nostrils) = 0 Pa, (2) air velocity at the walls = 0 m/s, and (3) a patient-specific outlet pressure. The post-surgery outlet pressure was such that the inhalation rate expected based on body mass (see below) was achieved. The pre-surgery outlet pressure was such that the transnasal pressure drop (nostrils to choana) was the same in the pre- and post-surgery models. This is important because the soft palate can have different configurations in the pre- and post-surgery scans leading to different nasopharynx resistances in the pre- and post-surgery models, which can confound the results when the same outlet pressure is imposed on all models (Borojeni et al., 2016; Kim et al., 2013). In other words, inhalation rates were different in the pre- and post-surgery models, but the pressure drop (nostrils to choana) was the same in each subject.