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Correlation of Nasal Mucosal Temperature With Subjective Nasal Patency in Healthy Individuals

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Abstract

Importance—Historically, otolaryngologists have focused on nasal resistance to airflow and minimum airspace cross-sectional area as objective measures of nasal obstruction using methods such as rhinomanometry and acoustic rhinometry. However, subjective sensation of nasal patency may be more associated with activation of cold receptors by inspired air than with respiratory effort.

Objective—To investigate whether subjective nasal patency correlates with nasal mucosal temperature in healthy subjects.

Design, Setting, and Participants—Twenty-two healthy adults were recruited for this study. Subjects first completed the Nasal Obstruction Symptom Evaluation (NOSE) and a unilateral visual analog scale (VAS) to quantify subjective nasal patency. A miniaturized thermocouple sensor was then used to record nasal mucosal temperature bilaterally in two locations along the nasal septum: at the vestibule and across from the inferior turbinate head.

Results—The range of temperature oscillations during the breathing cycle, defined as the difference between end-expiratory and end-inspiratory temperatures, was greater during deep breaths ($T_{\text{exp-insp}} = 6.2 \pm 2.6^\circ\text{C}$) than during resting breathing ($T_{\text{exp-insp}} = 4.2 \pm 2.3^\circ\text{C}$) in both locations ($p < 10^{-13}$). Mucosal temperature measured at the right vestibule had a statistically significant correlation with both right-side VAS score (Pearson $r = -0.55$, $p = 0.0076$) and NOSE

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Development and testing of temperature sensor: Bailey, Garcia, Pawar

IRB approval and subject recruitment: Bailey, Garcia

Data collection: All authors

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Manuscript review and approval: All authors

Study supervision: Garcia

Dr. Garcia had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

score (Pearson $r = -0.47$, $p = 0.028$). No other statistically significant correlations were found between mucosal temperature and subjective nasal patency scores. Nasal mucosal temperature was lower in the first cavity to be measured, which was the right cavity in all subjects.

Conclusions and Relevance—The greater mucosal temperature oscillations during deep breathing is consistent with the common experience that airflow sensation is enhanced during deep breaths, thus supporting the hypothesis that mucosal cooling plays a central role in nasal airflow sensation. A possible correlation was found between subjective nasal patency scores and nasal mucosal temperature, but our results were inconsistent. The higher temperature in the left cavity suggests that the sensor irritated the nasal mucosa, affecting the correlation between patency scores and mucosal temperature. Future studies should consider non-contact temperature sensors to prevent mucosa irritation.

Keywords

Subjective nasal patency; nasal airflow sensation; nasal mucosal temperature; mucosal cooling; NOSE score; visual analog scale; nasal airway obstruction

Introduction

Several objective techniques exist to quantify nasal airflow and nasal anatomy, including rhinomanometry, acoustic rhinometry, and peak nasal inspiratory flow (PNIF).^{1–4} These techniques have been used to demonstrate improved nasal patency in most patients undergoing nasal airway obstruction (NAO) surgery.^{5,6} However, these techniques have not been universally adopted for surgical planning due to low correlation with subjective nasal patency.⁷ The development of an objective test with better correlation to subjective nasal patency could improve NAO surgical outcomes by identifying patients who are unlikely to benefit from surgery.

Evidence suggests that the main mechanism of nasal airflow sensation is not airflow resistance, but rather mucosal cooling by inspired air.⁸ This dissociation between subjective perception of nasal airflow and objective nasal resistance is illustrated by the fact that subjects exposed to menthol vapor report improvement of nasal patency without any changes in nasal resistance.^{9–11} Recently, the menthol-sensitive cold receptors were identified as the transient receptor potential cation channel subfamily M, member 8 (TRPM8).¹² Data suggests that TRPM8 receptors are uniformly distributed on the nasal mucosa.^{13,14} Given that subjective nasal patency has a better correlation with mucosal cooling than airflow resistance, the question arises of how to quantify mucosal cooling reliably and whether an objective test can be developed for NAO surgical planning based on objective measures of mucosal cooling.

Recent computational studies demonstrated that it is possible to quantify inspiratory mucosal heat loss utilizing computational fluid dynamics (CFD) simulations in 3-dimensional patient-specific models of the nasal anatomy built from radiologic imaging.^{15–18} These computational studies confirmed that subjective nasal patency correlates better with mucosal heat loss than with nasal resistance to airflow.^{16,18} The CFD technique, however, has some disadvantages, including the high cost of medical imaging, radiation exposure when based

on computed tomography, the requirement of an expert operator, and the time delay required to obtain the medical images and run the simulations. To achieve broad applicability in clinical practice, the ideal objective exam would be fast, inexpensive, require minimum patient cooperation, require minimum operator skill, and reliably provide accurate measures of nasal mucosa cooling.

The aim of our study was threefold. First, nasal mucosal temperature was measured at two sites within the anterior nasal cavity of healthy individuals, thus contributing to the sparse literature on this topic. Second, nasal mucosal temperature was recorded during resting breathing vs. deep breathing and the results used to test the hypothesis that higher airflow during deep breathing is associated with lower mucosal temperatures. Finally, validated questionnaires were used to quantify subjective nasal patency and the results used to test the hypothesis that subjective nasal patency correlates with nasal mucosal temperature.

Methods

Subjects

The Institutional Review Board at the Medical College of Wisconsin approved this study with informed consent obtained from each subject. Twenty-two non-smoking healthy volunteers (12 males and 10 females; mean age 28.3 ± 7.0 years) were recruited for this study. A total of 44 nasal cavities were measured (left and right cavities for each patient). Exclusion criteria included history of nasal obstruction, nasal surgery, or smoking, current symptoms of cold or sinus infection, or current fever (defined as oral temperature $\geq 38.0^{\circ}\text{C}$ at the time of measurement).

Temperature Sensor

The temperature sensor and measurement protocol were similar to the method described by Lindemann and colleagues.^{19,20} Nasal mucosal temperature was measured with a T-type thermocouple (copper/constantan, range -200°C to $+350^{\circ}\text{C}$, sensitivity $43 \mu\text{V}/^{\circ}\text{C}$) with a probe tip outer diameter of 0.33 mm (Measurement Specialties, Inc, Hampton, VA, USA). The miniaturized thermocouple was connected to an acquisition interface box developed in-house that converted the thermocouple voltage to a temperature value. This temperature value was then sent to a laptop computer via USB interface for storage and display via a graphical interface developed in Matlab™ (MathWorks, Natick, MA). The system was verified and calibrated against a laboratory thermometer (Fluke Inc, Everett, WA, USA) to $<0.25^{\circ}\text{C}$ accuracy in the range of 0°C to 50°C .

Measurement Protocol

All subjects were measured with the following protocol. Subjects spent 30 minutes acclimating to room air before measurements. During this time, informed consent was completed, medical history was reviewed to assess for exclusion criteria, and subjects were administered the Nasal Obstruction Symptom Evaluation (NOSE) and unilateral Visual Analog Scale (VAS) questionnaire to assess subjective perception of nasal patency. Next, the subject was seated in a chair for measurement and a baseline oral temperature was recorded. The miniaturized thermocouple was inserted into the nasal cavity under direct visualization

by means of a nasal speculum and a headlight. No decongestants or local anesthetic were applied. The probe was lightly positioned against the septal mucosa and held in place by a trained otolaryngologist to ensure anatomical site and technique consistency between subjects. Mucosal temperature was recorded during quiet breathing for 60 seconds at two sites on the nasal septum, namely at the nasal vestibule (Site 1) and across from the head of the inferior turbinate (Site 2) (Figure 1). For Site 2, patients were asked to complete 3 deep breathing cycles (inhalation and exhalation) following the initial 60 seconds of quiet breathing. Inhalation rate was not recorded, but greater respiratory effort during deep breathing was verified by audible respiratory sounds. Both nasal cavities were measured, with the right cavity always measured first. Each subject completed measurement in approximately 6 minutes to avoid changes in nasal airflow related to the nasal cycle. Measurements were performed on four different days (each subject was measured only once). While room air temperature was consistent on different days (average $23.6 \pm 0.3^{\circ}\text{C}$), room air humidity varied slightly among different sessions (average $35 \pm 15\%$).

The end-inspiratory and end-expiratory nasal mucosal temperatures (T_{insp} and T_{exp}) were defined, respectively, as the minimum and maximum temperatures in each breathing cycle. This definition is based on a previous study by Lindemann and colleagues,²⁰ who recorded nasal mucosal temperature and chest motion simultaneously and reported that the minimum mucosal temperature coincided with the end of inspiration, while the maximum mucosal temperature coincided with the end of expiration. The last 3 breathing cycles of each 60-second recording were selected for analysis (except when comparing the first 3 breathing cycles vs. the last 3 breathing cycles). It was reasoned that analyzing the last 3 breaths during a 60-second recording would help mitigate the effect of awareness of breathing, which has been shown to alter the spontaneous breathing pattern, particularly via prolongation of inspiratory and expiratory times.²¹

Patient-Reported Assessment of Nasal Patency

To assess subjective nasal patency, all subjects completed the Nasal Obstruction Symptom Evaluation (NOSE), a validated questionnaire that quantifies symptoms of nasal airway obstruction (NAO) with a score ranging from 0 (no symptoms) to 100 (severe symptoms).^{22–24} Subjects also filled out a unilateral visual analog scale (VAS) evaluation for nasal airflow. Subjects were asked to cover one nostril and evaluate their ability to breathe through the uncovered nostril on a scale of 0 (completely clear) to 10 (completely obstructed). The VAS score is used primarily to assess instantaneous patency of the nasal airway at the time of measurement, as opposed to the NOSE score, which assesses nasal obstruction over the past month.

Statistical analysis

Two-tailed paired Student's t-tests were used to test whether differences in mucosal temperatures were statistically different. Differences were considered statistically significant for p-values < 0.05 . The correlation coefficients between subjective scores and mucosal temperature were computed using Pearson's correlation coefficient, while the trend lines were obtained by a least-squares linear regression.

Results

Our sample of 22 healthy individuals had an average NOSE score of 5.9 ± 8.4 (range 0–30) and average unilateral VAS score of 1.2 ± 1.4 (range 0–5). NOSE scores correlated with unilateral VAS scores for the right cavity (Pearson $r = 0.64$; 95% confidence interval = [0.30, 0.84]; $p = 0.0013$), but not with VAS scores for the left cavity (Pearson $r = 0.18$; 95% confidence interval = [−0.26, 0.56]; $p = 0.43$).

Measurements of nasal mucosal temperature were successfully completed in all subjects. Two subjects demonstrated significant discomfort with the miniaturized thermocouple with frequent sneezes, but the majority of subjects did not sneeze during the measurement protocol. Nasal mucosal temperature displayed a cyclical pattern with lower temperatures during inspiration and higher temperatures during expiration (Figure 2A). End-expiratory temperature was significantly higher than end-inspiratory temperature at all sites ($p < 10^{-14}$). The range of temperature oscillations during the breathing cycle, defined as the temperature difference $T_{\text{exp-insp}} = T_{\text{exp}} - T_{\text{insp}}$, was not statistically different between sites ($T_{\text{exp-insp}} = 4.1 \pm 2.2^\circ\text{C}$ at site 1 and $4.2 \pm 2.3^\circ\text{C}$ at site 2; $p = 0.81$). Also, there was no statistically significant difference between inspiratory temperature between sites ($T_{\text{insp}} = 29.6 \pm 2.7^\circ\text{C}$ at site 1 and $T_{\text{insp}} = 30.0 \pm 2.3^\circ\text{C}$ at site 2; $p = 0.36$), but expiratory temperatures were slightly higher at site 2 ($T_{\text{exp}} = 33.7 \pm 2.2^\circ\text{C}$ vs. $T_{\text{exp}} = 34.1 \pm 1.8^\circ\text{C}$, respectively; $p = 0.042$) (Figure 3).

For measurements at Site 2, subjects were requested to perform three deep breaths after 60 seconds of recording at rest breathing (Figure 2A). During deep breaths, the temperature variation between end-inspiration and end-expiration increased ($T_{\text{exp-insp}} = 6.2 \pm 2.6^\circ\text{C}$ during deep breathing vs. $4.2 \pm 2.3^\circ\text{C}$ during resting breathing; $p < 10^{-13}$) (Figure 2B). Deep breathing reduced the end-inspiratory mucosal temperatures ($T_{\text{insp}} = 28.3 \pm 2.5^\circ\text{C}$ for deep breathing vs. $30.0 \pm 2.3^\circ\text{C}$ for resting breathing; $p < 10^{-10}$), while increasing slightly the end-expiratory mucosal temperature ($T_{\text{exp}} = 34.5 \pm 1.5^\circ\text{C}$ for deep breathing vs. $34.1 \pm 1.8^\circ\text{C}$ for resting breathing; $p = 0.0072$). These results confirm our hypothesis that higher airflow during deep breathing is associated with lower inspiratory mucosal temperatures.

Our data suggest that insertion of the miniaturized thermocouple into the nasal cavity led to an increase in the nasal mucosal temperature in several patients. In a few cases, mucosal temperature showed a clear rising average during the 60 seconds of recording (Figure 4A), particularly at Site 1, but in most cases, the temperature increase was more subtle. Comparing the average end-inspiratory temperature during the first three breaths vs. last three breaths revealed a statistically significant rise in nasal mucosal temperature during the 60 seconds of recording at site 1 in the left cavity, but not at any other location (Figure 4B). Since temperature measurements were consistently performed first on the right cavity, followed by measurements on the left cavity, a comparison of mucosal temperatures on the two cavities provides an opportunity to test whether the miniaturized thermocouple elicited a thermal response in the nasal mucosa. Both the end-inspiratory and end-expiratory mucosal temperatures were approximately 1.5°C higher in the left cavity as compared to the right cavity [(T_{insp})_{left-right} = $1.5 \pm 3.4^\circ\text{C}$, $p = 0.0042$; (T_{exp})_{left-right} = $1.4 \pm 1.7^\circ\text{C}$, $p < 10^{-5}$], but there was no statistically significant difference in the range of temperature oscillations

during the breathing cycle between the two cavities [$(T_{\text{exp-insp}})_{\text{left-right}} = -0.1 \pm 3.5^{\circ}\text{C}$, $p=0.84$]. Altogether, these observations imply that nasal mucosal temperature increased during the course of the experiments in several subjects. This temperature increase affected both the end-inspiratory and end-expiratory mucosal temperatures, but not the average expiratory-to-inspiratory temperature difference $T_{\text{exp-insp}}$.

Correlation analysis comparing subjective nasal patency scores to mucosal temperature was performed at all sites (Figure 5). The range of nasal mucosal temperature oscillations ($T_{\text{exp-insp}}$) measured at the right vestibule had a statistically significant correlation with both right-side VAS score (Pearson $r = -0.55$; 95% confidence interval = $[-0.79, -0.17]$; $p=0.0076$) and NOSE score (Pearson $r = -0.47$; 95% confidence interval = $[-0.74, -0.06]$; $p=0.028$). No other statistically significant correlations were found between $T_{\text{exp-insp}}$ and subjective patency scores (Figure 5).

Discussion

Currently, the gold-standard objective measure of nasal patency is nasal resistance obtained via rhinomanometry.²⁵ However, there is growing evidence that the primary physiologic mechanism of nasal airflow sensation is nasal mucosal cooling, rather than airflow resistance.^{8,16,17,26} Given that objective measures of nasal resistance are rarely used in clinical decision-making due to their inconsistent correlation with subjective nasal patency,⁷ greater understanding of the physiologic mechanism of nasal airflow sensation is needed.

Unlike body temperature, which is fixed at 37°C , the temperature of the nasal mucosa is dynamic. It oscillates within each breathing cycle around an average temperature which is determined by various factors, including ambient air temperature and humidity,^{27–30} nasal infection,^{31,32} body posture,³³ and age,³⁴ among other factors.^{35,36} Lindeman and colleagues measured the nasal mucosal temperature on the nasal septum using a miniaturized thermocouple in 15 healthy individuals and reported an end-inspiratory temperature of $30.2 \pm 1.7^{\circ}\text{C}$ and an end-expiratory temperature of $32.5 \pm 1.1^{\circ}\text{C}$ in the nasal valve area.²⁰ Their results, which were obtained under similar room temperature ($25 \pm 1^{\circ}\text{C}$) and relative humidity ($30 \pm 4\%$) as in our study, are generally consistent with our results (Figure 3). In a subsequent publication, Lindemann and colleagues reported that nasal mucosal temperature correlates strongly with inhalation rate measured via rhinomanometry.¹⁹ A correlation between nasal mucosal temperature and inhalation rate was also reported by Willatt.³⁰ Although these studies quantified nasal mucosal temperature under different conditions, the role of nasal mucosal temperature in sensation of nasal airflow remains poorly understood.

Given that nasal mucosal temperature may be the primary mechanism of nasal airflow sensation, we hypothesize that the symptom of nasal obstruction is associated with an abnormally high mucosal temperature in NAO patients. However, to the best of our knowledge, this hypothesis has never been tested by direct measurements of nasal mucosal temperature in NAO patients vs. healthy individuals. Using CFD models, our group demonstrated that nasal patency scores correlate with mucosal heat loss in a cohort of surgical NAO patients.^{16,17} A similar correlation between subjective nasal patency and CFD-

derived mucosal heat loss was reported for healthy individuals by Zhao and colleagues.¹⁸ Krzych-Falta and coauthors used optical rhinometry to record blood flow in nasal vessels in 30 allergic patients and 30 healthy controls during a nasal allergen provocation test.³⁵ They reported that allergen exposure led to an increase in blood flow with a 3-min delay, which correlated with increased sensation of nasal congestion. We speculate that increased blood flow in nasal vessels increases the temperature of the nasal mucosa, thus contributing to the sensation of nasal congestion elicited by allergen exposure.

To our knowledge, the only previous study that correlated in vivo measurements of nasal mucosal temperature to subjective scores of nasal patency was performed by Willatt and Jones.³⁷ These researchers measured nasal mucosal temperature with a non-contact infrared sensor and reported a statistically significant correlation between mucosal temperature and VAS scores. In our study, the correlation between subjective nasal patency scores and nasal mucosal temperature was inconsistent. A statistically significant correlation was found between both NOSE and VAS with $T_{\text{exp-insp}}$ measured on the right vestibule, but this correlation was not found in any other site (Figure 5). There are several possible explanations for these inconsistent results. One possibility is that the miniaturized thermocouple irritated the nasal mucosa eliciting a thermal response (Figure 4), thus confounding the correlation between mucosal temperature and subjective scores. The fact that the right vestibule was the first site to be measured in all patients is consistent with this hypothesis, since measurements at this site would be the least affected by the consequences of mucosal irritation. However, the mean difference between end-inspiratory and end-expiratory temperatures was not significantly affected by mucosal irritation, suggesting that other factors may be at play.

Another possibility is that the NOSE and VAS scores, although universally used in the literature, are imperfect measures of subjective nasal patency. In our study, more than half of subjects (12 out of 22) had a NOSE score of 0, while 6 out of 22 subjects reported a VAS score of 0 for both cavities. This cluster of zero-valued scores would reduce the correlation with any objective measure of nasal patency. In addition, the lack of correlation between NOSE scores and left-side VAS scores in our study suggests that these questionnaire-based scores are very noisy, particularly at the low obstruction levels seen in healthy subjects.⁷ For future studies, a better strategy would be to quantify nasal mucosal temperature before and after an intervention, such as nasal surgery or exposure to cold air. An intervention provides an anchor for the subjective sensation of nasal patency,²⁶ which may improve the correlation between subjective patency scores and objective measures of nasal airflow.

A potential limitation of our study, and other studies utilizing contact temperature sensors, was the observation of nasal mucosa irritation. Measurements were always carried out first on the right cavity, followed by the left cavity, and mucosal temperatures were significantly higher on the left cavity. In some cases, a gradual rise in the average temperature was clearly observed over the course of measurement (Figure 4). Operator discomfort in holding the temperature sensor at a fixed point over an extended period of measurement sometimes led to variations in the pressure imposed on the sensor, thus contributing to mucosal irritation. It is possible that some participants suppressed their breathing as they tried to ignore the irritating stimulus. Although Lindemann and coauthors stated that mucosal irritation was not

observed in their study,²⁰ mucosal irritation with concomitant increase in nasal mucosal temperature was observed in other studies using contact temperature sensors.^{30,31} Thus, we suggest that future studies should consider non-contact sensors for recording nasal mucosal temperature.^{30,37}

Another limitation of our study is that mucosal swelling was not tracked. It is possible that, by irritating the nasal mucosa, the temperature sensor caused mucosal swelling, affecting the airflow rate. Future studies should consider investigating changes in nasal mucosal temperature during the nasal cycle. In theory, nasal mucosal temperature is lower in the decongested side, where airflow is higher. Thus, one should expect oscillations in nasal mucosal temperature in synchrony with the nasal cycle.

In summary, more investigation is needed into the temperature dynamics of the nasal mucosa and its role in nasal airflow sensation. This study confirms that a higher inhalation rate during deep breathing is associated with lower end-inspiratory nasal mucosal temperature. This quantitative observation is consistent with the common experience that airflow sensation is enhanced during deep breaths, thus supporting the hypothesis that mucosal cooling plays a central role in nasal airflow sensation. However, the correlation between nasal patency scores and mucosal temperature was inconsistent and likely confounded by the miniaturized thermocouple irritating the mucosa. Our observations suggest that two strategies could be used in future studies to clarify the role of nasal mucosal temperature in subjective nasal patency, namely (1) non-contact temperature sensors can be used to prevent mucosa irritation and (2) nasal mucosal temperature can be measured before and after an intervention, such as nasal surgery or exposure to cold air. A better understanding of the physiologic mechanism of nasal airflow sensation could lead to more accurate objective methods to assess nasal patency and eventually to better outcomes for NAO surgery.^{38–40}

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References

1. Hilberg O, Jackson AC, Swift DL, Pedersen OF. Acoustic rhinometry: evaluation of nasal cavity geometry by acoustic reflection. *Journal of Applied Physiology*. 1989; 66:295–303. [PubMed: 2917933]
2. Bermuller C, Kirsche H, Rettinger G, Riechelmann H. Diagnostic accuracy of peak nasal inspiratory flow and rhinomanometry in functional rhinosurgery. *Laryngoscope*. 2008; 118:605–610. [PubMed: 18176341]
3. Cole P, Roithmann R, Roth Y, Chapnik JS. Measurement of airway patency. A manual for users of the Toronto systems and others interested in nasal patency measurement. *Ann Otol Rhinol Laryngol Suppl*. 1997; 171:1–23. [PubMed: 9345161]

4. Clement PA, Gordts F. Standardisation Committee on Objective Assessment of the Nasal Airway IRS. Consensus report on acoustic rhinometry and rhinomanometry. *Rhinology*. 2005; 43:169–179. [PubMed: 16218509]
5. Moore M, Eccles R. Objective evidence for the efficacy of surgical management of the deviated septum as a treatment for chronic nasal obstruction: a systematic review. *Clin Otolaryngol*. 2011; 36:106–113. [PubMed: 21332671]
6. Holmstrom M. The use of objective measures in selecting patients for septal surgery. *Rhinology*. 2010; 48:387–393. [PubMed: 21442073]
7. Andre RF, Vuyk HD, Ahmed A, Graamans K, Nolst Trenite GJ. Correlation between subjective and objective evaluation of the nasal airway. A systematic review of the highest level of evidence. *Clin Otolaryngol*. 2009; 34:518–525. [PubMed: 20070760]
8. Sozansky J, Houser SM. The physiological mechanism for sensing nasal airflow: a literature review. *Int Forum Allergy Rhinol*. 2014; 4:834–838. [PubMed: 25079504]
9. Eccles R, Griffiths DH, Newton CG, Tolley NS. The effects of menthol isomers on nasal sensation of airflow. *Clin Otolaryngol Allied Sci*. 1988; 13:25–29. [PubMed: 3370851]
10. Burrow A, Eccles R, Jones AS. The effects of camphor, eucalyptus and menthol vapour on nasal resistance to airflow and nasal sensation. *Acta Otolaryngol*. 1983; 96:157–161. [PubMed: 6613544]
11. Eccles R, Jones AS. The effect of menthol on nasal resistance to air flow. *J Laryngol Otol*. 1983; 97:705–709. [PubMed: 6886530]
12. Bautista DM, Siemens J, Glazer JM, et al. The menthol receptor TRPM8 is the principal detector of environmental cold. *Nature*. 2007; 448:204–208. [PubMed: 17538622]
13. Meusel T, Negoias S, Scheibe M, Hummel T. Topographical differences in distribution and responsiveness of trigeminal sensitivity within the human nasal mucosa. *Pain*. 2010; 151:516–521. [PubMed: 20817356]
14. Liu SC, Lu HH, Cheng LH, et al. Identification of the cold receptor TRPM8 in the nasal mucosa. *Am J Rhinol Allergy*. 2015; 29:e112–e116. [PubMed: 26163239]
15. Dayal A, Rhee JS, Garcia GJM. Impact of Middle vs. Inferior Total Turbinectomy on Nasal Aerodynamics. *Otolaryngology Head and Neck Surgery*. 2016 in press.
16. Kimbell JS, Frank DO, Laud P, Garcia GJ, Rhee JS. Changes in nasal airflow and heat transfer correlate with symptom improvement after surgery for nasal obstruction. *J Biomech*. 2013; 46:2634–2643. [PubMed: 24063885]
17. Sullivan CD, Garcia GJ, Frank-Ito DO, Kimbell JS, Rhee JS. Perception of better nasal patency correlates with increased mucosal cooling after surgery for nasal obstruction. *Otolaryngol Head Neck Surg*. 2014; 150:139–147. [PubMed: 24154749]
18. Zhao K, Jiang J, Blacker K, et al. Regional peak mucosal cooling predicts the perception of nasal patency. *Laryngoscope*. 2014; 124:589–595. [PubMed: 23775640]
19. Lindemann J, Keck T, Scheithauer MO, Leiacker R, Wiesmiller K. Nasal mucosal temperature in relation to nasal airflow as measured by rhinomanometry. *Am J Rhinol*. 2007; 21:46–49. [PubMed: 17283560]
20. Lindemann J, Leiacker R, Rettinger G, Keck T. Nasal mucosal temperature during respiration. *Clin Otolaryngol Allied Sci*. 2002; 27:135–139. [PubMed: 12071984]
21. Han JN, Stegen K, Cauberghs M, Van de Woestijne KP. Influence of awareness of the recording of breathing on respiratory pattern in healthy humans. *Eur Respir J*. 1997; 10:161–166. [PubMed: 9032510]
22. Stewart MG, Smith TL, Weaver EM, et al. Outcomes after nasal septoplasty: results from the Nasal Obstruction Septoplasty Effectiveness (NOSE) study. *Otolaryngol Head Neck Surg*. 2004; 130:283–290. [PubMed: 15054368]
23. Stewart MG, Witsell DL, Smith TL, Weaver EM, Yueh B, Hannley MT. Development and validation of the Nasal Obstruction Symptom Evaluation (NOSE) scale. *Otolaryngol Head Neck Surg*. 2004; 130:157–163. [PubMed: 14990910]
24. Rhee JS, Sullivan CD, Frank DO, Kimbell JS, Garcia GJ. A systematic review of patient-reported nasal obstruction scores: defining normative and symptomatic ranges in surgical patients. *JAMA Facial Plast Surg*. 2014; 16:219–225. quiz 232. [PubMed: 24604253]

25. Schumacher MJ. Nasal dyspnea: the place of rhinomanometry in its objective assessment. *Am J Rhinol.* 2004; 18:41–46. [PubMed: 15035570]
26. Zhao K, Blacker K, Luo Y, Bryant B, Jiang J. Perceiving nasal patency through mucosal cooling rather than air temperature or nasal resistance. *PLoS One.* 2011; 6:e24618. [PubMed: 22022361]
27. Drettner B. Analysis of the blood flow in the nasal mucosa on exposure to cold. *Acta Otolaryngologica.* 1961; (Supplement 166, Chapter VII):85–95.
28. Cole P. Further observations on the conditioning of respiratory air. *J Laryngol Otol.* 1953; 67:669–681. [PubMed: 13109356]
29. Webb P. Air temperatures in respiratory tracts of resting subjects in cold. *J Appl Physiol.* 1951; 4:378–382. [PubMed: 14938268]
30. Willatt DJ. Continuous infrared thermometry of the nasal mucosa. *Rhinology.* 1993; 31:63–67. [PubMed: 8362171]
31. Akerlund A, Bende M. Nasal mucosal temperature and the effect of acute infective rhinitis. *Clin Otolaryngol Allied Sci.* 1989; 14:529–534. [PubMed: 2612033]
32. Bende M, Barrow I, Heptonstall J, et al. Changes in human nasal mucosa during experimental coronavirus common colds. *Acta Otolaryngol.* 1989; 107:262–269. [PubMed: 2538995]
33. Molony N, Blackwell CC, Busuttill A. The effect of prone posture on nasal temperature in children in relation to induction of staphylococcal toxins implicated in sudden infant death syndrome. *FEMS Immunol Med Microbiol.* 1999; 25:109–113. [PubMed: 10443498]
34. Molony NC, Kerr AI, Blackwell CC, Busuttill A. Is the nasopharynx warmer in children than in adults? *J Clin Forensic Med.* 1996; 3:157–160. [PubMed: 15335601]
35. Krzych-Falta E, Sybilski A, Wojas O, Samolinski B. Optical rhinometry in nasal provocation testing. *Postepy Dermatol Alergol.* 2015; 32:449–454. [PubMed: 26755909]
36. Assanasen P, Baroody FM, Naureckas E, Naclerio RM. Warming of feet elevates nasal mucosal surface temperature and reduces the early response to nasal challenge with allergen. *J Allergy Clin Immunol.* 1999; 104:285–293. [PubMed: 10452746]
37. Willatt DJ, Jones AS. The role of the temperature of the nasal lining in the sensation of nasal patency. *Clin Otolaryngol Allied Sci.* 1996; 21:519–523. [PubMed: 9118573]
38. Garcia GJ, Hariri BM, Patel RG, Rhee JS. The relationship between nasal resistance to airflow and the airspace minimal cross-sectional area. *J Biomech.* 2016; 49:1670–1678. [PubMed: 27083059]
39. Hariri BM, Rhee JS, Garcia GJ. Identifying patients who may benefit from inferior turbinate reduction using computer simulations. *Laryngoscope.* 2015; 125:2635–2641. [PubMed: 25963247]
40. Rhee JS, Pawar SS, Garcia GJ, Kimbell JS. Toward personalized nasal surgery using computational fluid dynamics. *Arch Facial Plast Surg.* 2011; 13:305–310. [PubMed: 21502467]

FIGURE 1. Diagram of the sites measured

Nasal mucosal temperature was measured at (1) the nasal septum at the nasal vestibule and (2) the nasal septum across from the head of the inferior turbinate. Dotted lines show the location of the nasal turbinates and the junction between squamous and respiratory epithelium near the nasal valve.

FIGURE 2. Higher inhalation rate during deep breathing increases the range of nasal mucosal temperature oscillations during the breathing cycle

(A) Nasal mucosal temperature versus time recorded at the nasal septum across from the inferior turbinate in one healthy volunteer, showing typical temperature variation during the respiratory cycle for quiet breathing and deep breathing. (B) The range of temperature oscillations during the breathing cycle (i.e., the difference $T = T_{\text{exp}} - T_{\text{insp}}$, where T_{exp} is the end-expiratory temperature and T_{insp} is the end-inspiratory temperature) was greater during deep breathing than during quiet breathing. The asterisk (*) denotes a statistically significant difference ($p < 10^{-13}$).

FIGURE 3. Average nasal mucosal temperature in healthy subjects

Mean and standard deviation for end-inspiratory and end-expiratory temperatures for the left and right nasal cavities at measured sites, including deep breathing measurements.

FIGURE 4. The miniaturized thermocouple irritated the nasal mucosa in some subjects
 (A) In a few cases, nasal mucosal temperature displayed a raising average trend during the 60 seconds of recording. (B) Comparison of the end-inspiratory temperature (T_{insp}) in the first 3 breaths versus the last 3 breaths of the recording. A statistically significant rise in temperature was observed at the left vestibule ($p = 0.0087$).

FIGURE 5. Correlation between unilateral VAS scores with the difference between end-expiratory and end-inspiratory nasal mucosal temperatures ($T_{\text{exp-insp}}$)
 Only $(T_{\text{exp-insp}})$ measured on the right vestibule had a statistically significant correlation with subjective nasal patency (Pearson $r = -0.55$; $p = 0.0076$).