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Review Article

Air-conditioning characteristics of the human nose

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Abstract
Nasal inspiration is important for maintaining the internal milieu of the lung, since ambient air is conditioned to nearly alveolar conditions (body temperature and fully saturated with water vapour) upon reaching the nasopharynx. This literature review of the existing *in vivo*, *in vitro* and computational studies on transport phenomena that take place within the human nasal cavity summarizes the current knowledge on air-conditioning characteristics of the human nose.

Key words: Nasal Cavity; Physiology; Air Conditioning

Introduction

Humans can live in tropical or arctic climates as well as shift from one extreme environment to another within very short periods of time without injuring the respiratory system. The nasal cavity equilibrates inspired air with interior body conditions with remarkable efficiency in order to protect the internal milieu of the lung. Inspiration through the nasal cavity conditions the ambient air to nearly alveolar conditions (i.e., being fully saturated with water vapour and at the same body temperature) by the time it reaches the pharynx.

Nasal anatomy and physiology

The nose is part of the upper airways and has a complex three-dimensional geometry. The passageway for air narrows at the nasal valve and widens as it reaches the mid-section at the site of the nasal turbinates.[1–4] The inner surface of the nasal cavity is lined with a ciliated highly vascularized mucosa, which is rich in mucosal glands and goblet cells.[1,4] The nasal cavity is enclosed by four groups of air-filled paranasal sinuses, which are also lined with mucus and are normally connected with the air in the nasal passages.[5,6]

At rest, humans respire mainly through their nose at 12–15 breaths per minute (about 10 000 litres of air in one day.[4,7] During quiet breathing, the resistance of the nasal passage is about one-half that of the entire respiratory tract, and about 50 per cent more effort is required compared to mouth breathing. The pressure drop across the nasal cavity is estimated to be between 0.3 to 1.3 cmH_2O.[8] The main physiological functions of the nose are:[2,4,8–13]

(1) *Filtration* Nearly all particles greater than 5 μm and about 50 per cent of those from 2–4 μm in size are deposited on the ciliated mucosa and are propelled towards the pharynx so that they can be swallowed or expectorated within 15 minutes. Particles less than 2 μm pass through the nose into the lower airways;

(2) *Air-conditioning* Inspired air comes into contact with the warm and moist nasal mucosa and is rapidly warmed and humidified, while during expiration, some of the heat and water are returned to the nasal walls. For example, in a pleasant environment of 23°C and 40 per cent relative humidity, inhaled air is warmed to 33°C and humidified to 98 per cent relative humidity before reaching the glottis.

(3) *Olfaction* The respective sense organ is located at the roof of the nasal cavity.

Physics of air-conditioning

Atmospheric air contains a mixture of gases (e.g. nitrogen, oxygen), water vapour and miscellaneous contaminants. Dry air exists when all of the contaminants and water vapour have been removed from atmospheric air, and its volume contains about 78 per cent nitrogen, 21 per cent oxygen, and other gases. Moist or humid air is a mixture of dry air and water vapour. The water vapour capacity of air increases with the temperature. Air at saturation at a

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given temperature carries its maximal capacity of water (e.g. an equilibrium exists between the number of molecules evaporating, and the number of molecules condensing). The absolute humidity expresses the mass of water vapour content in a volume of air (for example, mgH_2O/L), while the relative humidity, expresses the ratio (in percentage) of the amount of water vapour in the air with the amount of water vapour that would be present in the air at saturation at the same temperature. Psychrometry is the study of moist air and of the changes in its conditions. The psychrometric chart graphically illustrates the relationships between air temperature and relative humidity, and is a basic design tool for engineers.

Air-conditioning is a transport process that controls the humidity and temperature of air. The transport patterns of air within a complex enclosure such as the nasal cavity are controlled by a set of four differential equations that include the conservation of material, equilibrium of forces, conservation of thermal energy and the convection-diffusion balance.[14] The solution of this set of governing equations provides the instantaneous spatial distribution of velocity, pressure, temperature and water vapour concentration, as well as the heat and water vapour flux from the walls, at any point of the simulated cycle of nasal breathing. The total heat flux from the nasal wall also includes the component of latent heat of evaporation, which represents the energy required to evaporate the water at the wall-gas interface in order to moisturize the inspired environmental air.

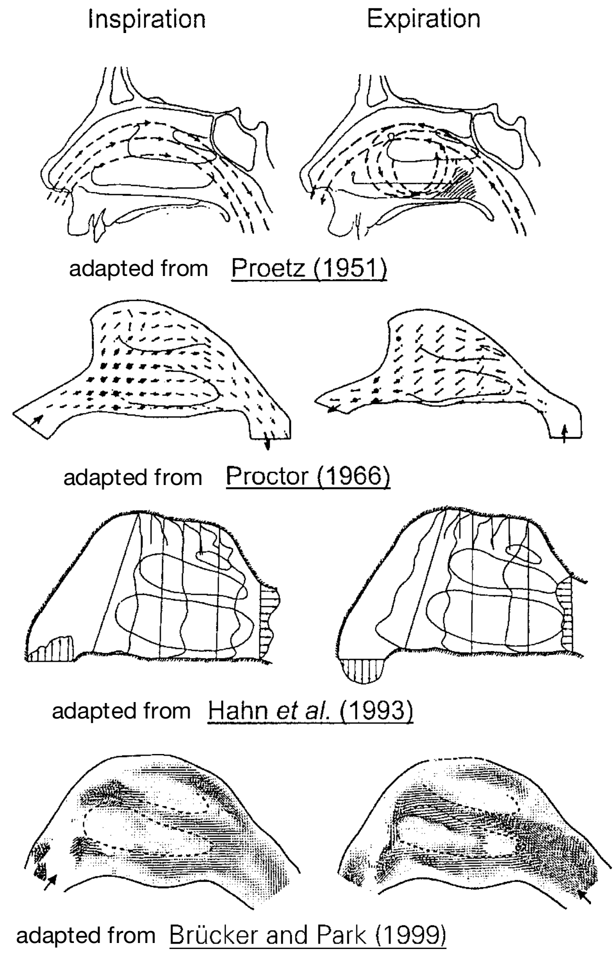

FIG. 1
Steady inspiratory and expiratory airflow pattern in the human nose.[8,16,19,20]

Air flow in the nasal cavity

The details of nasal airflow pattern were investigated either with laboratory models or by employing computer simulations due to the inaccessibility to the nasal cavity, which prevents *in vivo* studies. A summary of early works from the first half of the 20th century[15] indicated that air currents are practically laminar in the normal nose. Air enters the nares, rises fairly vertically along the bridge towards the anterior end of the middle turbinate, whereupon the current is deflected and passes between the middle turbinate and the septum (middle meatus) down towards the posterior end of the inferior turbinate. If the angle between the free edge of the septum and the upper lip is about 90° (as in normal Caucasians), the air current rises even higher. Local whirls (a turbulent-like phenomenon) may be generated downstream of bodies which protrude into the stream or sites of branching, but their degree (number and sizes) and rate of dissipation are yet unknown. Expiratory flow patterns are similar to those for inspiration.

Early *in vitro* models were made of either half heads or casts from human cadavers, in which the nasal septum was replaced with a transparent plate to enable visualization of flow. More recently, transparent models of the nasal cavity were manufactured from computed tomography (CT) images. Qualitative visualization of the nasal airflow pattern using smoke in a model without the inferior and middle turbinates revealed inspiratory airflow to take a sharp turn into the nasopharynx, while expiratory flow demonstrated a double eddy in the nasal chamber (Figure 1).[16] Quantitative measurements of local velocities with a miniature angle meter in an entire half-nasal model showed that airstream patterns of quiet inspiration are almost independent of the flow rate and are concentrated mainly in the middle meatus (Figure 1).[8,17] The inspiratory linear velocity is maximal at the nasal valve (6–18 m/s), decreases to 2 m/s in the main passage and increases again to 3 m/s in the nasopharynx. During expiration, the air speed is about 1–2 m/s and it is evenly distributed in the nasal cavity, with an increase (to about 3–6 m/s) at the nasal valve. Non-invasive measurements performed with a laser Doppler velocimeter during quiet breathing showed that airflow in the nose is mostly laminar and is streamlined by the turbinates, with greater velocities in the lower half of the cavity (up to 1.05 m/s anterior to the turbinates) and near the septum.[18] Local measurements with a hot-wire anemometer in a 20-fold large human nose (constructed from CT images) confirmed these earlier findings (Figure 1).[19] Employment of digital particle

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image velocimetry, which uses successive images of illuminated micro-scale particles in the moving fluid to visualize and analyse the flow field, revealed similar results (Figure 1), but suggested that a two-dimensional technique is short of providing an accurate description of the complex nasal airflow.[20]

Computer simulations of inspiratory airflow in the nasal cavity were conducted by utilizing numerical methods for airflow in complex enclosures. The geometry of the nasal cavity, obtained either from anatomical images (e.g. CT)[21–23] or a nose-like structure which resembles the complex geometry of the nasal cavity, enabled analysis of various parameters.[14,24] The results showed that the main flux of air tends to flow through the inferior and middle meatuses and along the floor of the nose, with the turbinates reducing the coronal cross-sectional areas and determining the paths for airflow. The trapezoidal shape in the coronal plane and the turbinates serve to direct the flow toward the olfactory region.

Air-conditioning in the nasal cavity

The gradient of temperature and humidity of respiratory gas between ambient conditions and the position along the respiratory tract, where core temperature and 100 per cent relative humidity are achieved, are dynamic over the breath cycle and vary with ambient conditions, nasal or oral breathing and pathological conditions.[25] A healthy human consumes up to 350 kcal of heat and 400 mL of water in one day to condition the inspired air at moderate environmental conditions (e.g. 25°C and 50 per cent relative humidity), and about a third of that is recovered during expirations.[10,11,26] *In vivo* measurements of air temperature within the upper respiratory tract throughout the respiratory cycle were acquired with a thermocouple that was introduced via the nose during fibre-optic bronchoscopy.[13,25,27–29] A representative summary of temperature and humidity distribution in the respiratory tract (Table I) for a healthy adult during quiet breathing at room temperature (22°C and 50 per cent relative humidity) shows that the nasal cavity heats the inspired air to about 34°C.[13,25,27,28] Inspiration of very cold air (e.g. –18°C) produces an air temperature of 30°C in the pharynx.[27] Recently, a technique was also developed to measure endonasal distributions of temperature and humidity.[30] While these findings are true for quiet breathing, at high levels of ventilation additional air-conditioning must take place in the intrathoracic airways in order to completely condition the inspired air to alveolar conditions.[31]

The first generation of mathematical models for simulations of heat and water vapour exchange in the nasal cavity were developed for simple channels or axisymmetric tubes, and they assumed quasi-steady inspiratory airflow.[27,32–36] A more recent unsteady transport model of inspiratory airflow through transverse cross-sections of the nasal cavity revealed that inhaled air is warmed and humidified to nearly 90 per cent of alveolar conditions before reaching the nasopharynx.[14] The turbinates increased the rate of local heat and moisture transport by improving mixing and by maintaining thin boundary layers. However, the instantaneous heat and water vapour transfer to the inspired air was significantly reduced during periods of increased air speed. Healthy noses can handle a range of extreme environments, but deficiency in blood supply or surface moistening may reduce the rate of heat or moisture flux into the inspired air. Overall, these studies confirmed the notion that there is ample time for heating and humidification in normal noses in normal environments.[37]

The nasal cavity performs most of the air-conditioning that equilibrates the inspired environmental air with alveolar conditions. In order to examine its efficacy, the flux of heat and water vapour that would bring all the inspired environmental air to alveolar conditions (e.g. 37°C and 100 per cent relative humidity) was calculated from psychrometric charts. The daily heat and water flux required to condition environmental air at different conditions (e.g. temperature ranging from 10°C to 45°C, and humidity from 0 per cent relative humidity to 100 per cent relative humidity) to alveolar conditions are demonstrated in Figure 2 for a healthy adult who breaths approximately 10 000 L/day (assuming a vital capacity of $V_T = 0.5$ L and $f = 15$ breaths/min). For example, the daily heat and water uptake by the inspired air at normal ambient air (e.g. 25°C and 20 per cent relative humidity) would be 265 kcal and 370 mL, respectively. As the relative humidity of the inspired air increases, the dependency of both heat and water uptake on ambient temperature also increases. However, for very dry ambient air (relative humidity approaches 0 per cent), the amount of water uptake required to bring the inspired air to alveolar conditions is independent of the ambient temperature, and heat transfer is very weakly dependent upon ambient temperature.

TABLE I

DISTRIBUTION OF TEMPERATURE AND HUMIDITY IN THE RESPIRATORY TRACT DURING QUIET BREATHING AT ROOM TEMPERATURE (22°C, 50 PER CENT RELATIVE HUMIDITY = 10 mgH_2O/L)[25]

	Inspiration		Expiration	
Location	Temperature [°C]	Humidity [mgH_2O/L]	Temperature [°C]	Humidity [mgH_2O/L]
Nares	22	10	32–34	27–34
Larynx	31–33	26–32	∀36	40
Mid-trachea	∀34	34–38	–	–
Main bronchi	37	44	37	44

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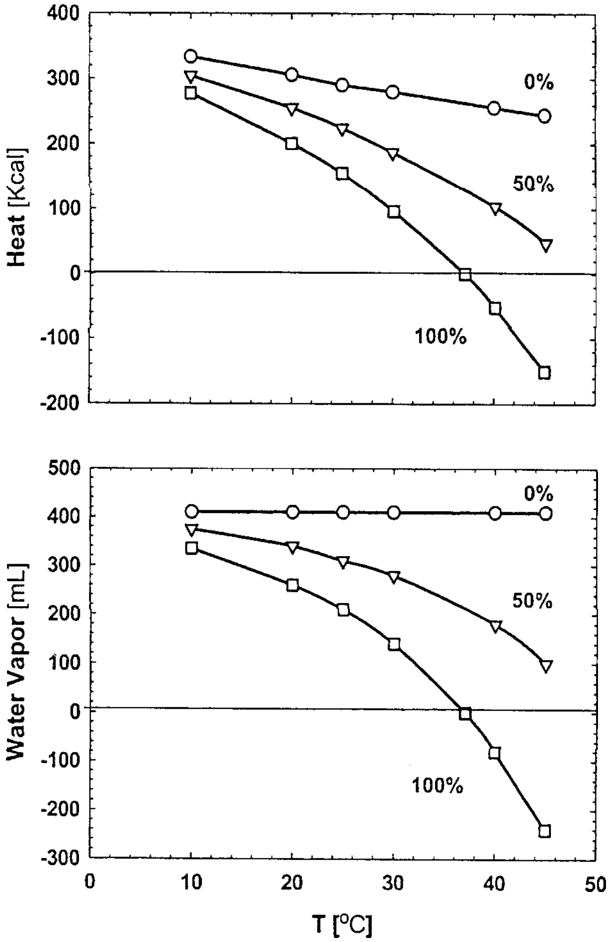

FIG. 2

Daily rates of heat and water vapour flux required to condition environmental air to alveolar conditions (37°C, 100 per cent relative humidity at normal breathing: $V_T = 0.5$ L, $f = 15$/min (about 10 000 L/day).

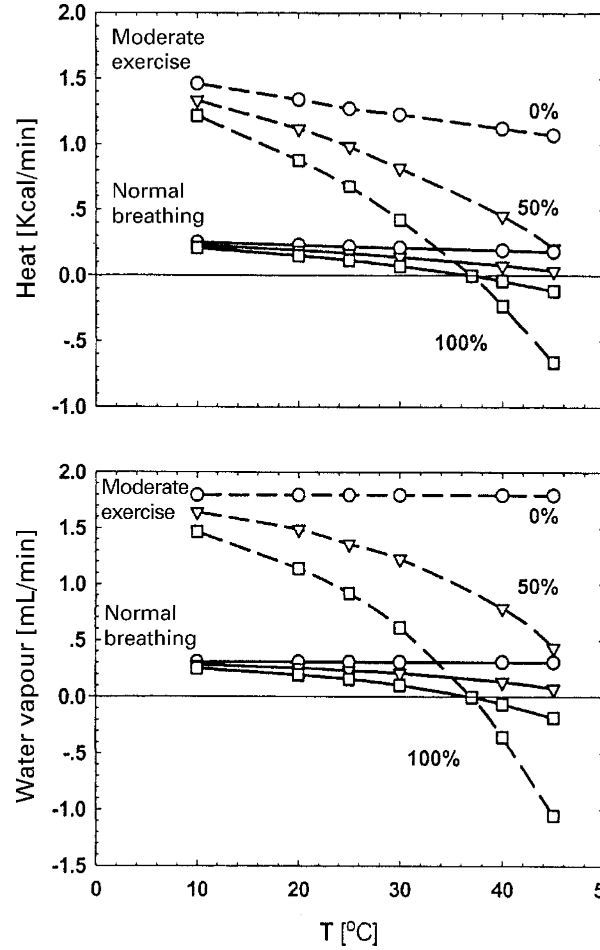

FIG. 3

Minute rates of heat and water vapour flux required to equilibrate environmental air to alveolar conditions (37°C, 100 per cent relative humidity). Normal breathing: $V_T = 0.5$ L, $f = 15$/min (7.5 L/min); moderate exercise: $V_T = 1.46$ L, $f = 30$/min (43.8 L/min). (Symbols: ○ = 0 per cent relative humidity; ▽ = 50 per cent relative humidity; □ = 100 per cent relative humidity).

- **This is largely a review of previous work looking at the air-conditioning characteristics of the nose**
- **The new material is limited to a theoretical prediction as to the amount of heat and water vapour that should be delivered into inspired air to condition it for the alveoli**
- **The paper provides a synopsis of various aspects of nasal physiology and of *in vitro* research that may be of value to otolaryngologists**

During exercise, the muscle demand for oxygen is greatly elevated and maximal ventilation ($V_T \times f$) may increase up to 30-fold when compared to resting values. In order to compare the transport needs of breathing during moderate exercise (e.g. $V_T = 1.46$L and $f = 30$/min) with respect to those in normal breathing, the heat and water vapour flux required to modify the inspired air to alveolar conditions in one minute were computed. The rates of heat and water vapour flux during normal quiet breathing (e.g. 7.5 L/min) and moderate exercise (e.g. 43.8 L/min) are depicted in Figure 3. The general patterns of heat and water vapour transport during exercise are seen to be similar to those in normal breathing, but by one order of magnitude larger, which is to be expected since a larger amount of air is consumed in exercise and more energy and water vapour are needed to heat and wet the inspired air to achieve alveolar conditions.

Pathophysiology and nasal air-conditioning

Medical and pharmaceutical as well as surgical interventions are presently being used at an increasing rate to restore nasal structure and function.[38] These interventions induce local changes that may affect the efficiency of heat and water vapour transport phenomena. However, the exact intra-nasal characteristics and distribution of these transport phenomena, as well as the effect of local changes as a response to intervention, remain unknown.

The effect of turbinectomy on nasal air-conditioning characteristics was recently explored by a computerized nose model.[39] The predicted simulations showed that removal of the inferior turbinate may reduce the heat and water vapour flux into the inspired ambient air by 16 per cent, while removal of the middle turbinate may result in a reduction of 12 per cent in comparison to these values for a healthy nose. Removal of both conchae reduces the heat and water vapour flux by 23 per cent. These losses may be partially recovered (approximately six per cent) by reconstruction of the inferior turbinate with artificial materials such as hydroxyapatite cement.[40]

Modification of nasal anatomy with age may also affect its air-conditioning capacity. A recent study revealed that endonasal changes in the elderly include gradual rising of the cavity volume, presumably induced by mucosal atrophy, that may hamper heat and vapour transport efficacy.[41] In addition, chronic respiratory and cardiovascular disorders may frequently be encountered in the aged population. The additive impact of these factors in regard to lung ventilation as well as nasal air-conditioning capacity warrants further investigation.

Future perspective

Disorders of nasal functioning due to obstruction or allergy are frequently encountered in the general population. The discrepancy between allegedly minor nasal dysfunction and the degree of misery is at times out of proportion to the theoretical deficit in function and the depending parameters for sensation of 'normal breathing' are not clear. The most popular objective techniques for measurement of nasal function (e.g. acoustic rhinometry, rhinomanometry) still render ambiguities and inconsistencies. Currently, computer models can accurately simulate airflow and air-conditioning capacity of the nose, but how these parameters affect nasal airflow sensation and cardiopulmonary receptors remains unknown. There is also a need to investigate the complex relationships between nasal airflow and the cellular responses within the delicate lining of the nasal walls. This may be helped by the development of software for custom modelling of nasal function based on medical images and other objective measurements for planning and monitoring of medical interventions.

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