Supine position decreases the ability of the nose to warm and humidify air

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Supine position decreases the ability of the nose to warm and humidify air. J Appl Physiol 91: 2459–2465, 2001.—We tested the hypothesis that decreasing nasal air volume (i.e., increasing nasal turbinate blood volume) improves nasal air conditioning. We performed a randomized, two-way crossover study on the conditioning capacity of the nose in six healthy subjects in the supine and upright position. Cold, dry air (CDA) was delivered to the nose via a nasal mask, and the temperature and humidity of air were measured before it entered and after it exited the nasal cavity. The total water gradient (TWG) across the nose was calculated and represents the nasal conditioning capacity. Nasal volume decreased significantly from baseline without changing the mucosal temperature when subjects were placed in the supine position (P < 0.01). TWG in supine position was significantly lower than that in upright position (P < 0.001). In the supine position, nasal mucosal temperature after CDA exposure was significantly lower than that in upright position (P < 0.01). Our data show that placing subjects in the supine position decreased the ability of the nose to condition CDA compared with the upright position, in contrast to our hypothesis.

nasal volume; nasal mucosal temperature

One of the primary functions of the nose is to warm and humidify air (19). We have developed a method to measure the ability of the nose to condition cold, dry air (CDA) (31). Theoretically, the two most important predicting parameters of the nasal air-conditioning process are the blood temperature distribution along the airway walls, or the nasal mucosal temperature, and the volume, or perimeter, of the nasal cavity (16). Our laboratory has previously shown that an increase in nasal mucosal temperature by feet warming increases the ability of the nose to warm and humidify air (1). How altering the other important parameter, nasal volume, affects nasal conditioning is the subject of this paper.

Assumption of the supine position has been consistently shown to increase nasal airway resistance (25, 37, 39) and decrease nasal volume (20) secondary to an increase in the volume of the capacitance vessels of the nose. Although actual blood volume in the cavernous sinusoids has not been measured in the upright and supine positions, an increase in nasal blood volume is the explanation given for the consistent changes in nasal cavity volume and nasal airway resistance. The logic of this statement is based on the fact that bone and cartilage surrounding the nasal cavity in the region of 2–6 cm from the inferior tip (the part measured by acoustic rhinomanometry) do not change in the time frame of the experiments. The only other structures within that region are the nasal mucosa with its cavernous sinusoids. Sinusoids are considered the variable responsible for the change in nasal cavity volume on changing from the upright to the supine position. Because the nasal cavity has defined anatomic limits, an increase in blood volume will lead to a reciprocal decrease in nasal cavity volume and vice versa. Supporting this notion is the effect of topical intranasal decongestants, which decrease nasal blood volume and increase nasal cavity volume (30, 40). We hypothesized, consistent with the hypothesis raised by Hanna and Scherer (16), that decreasing nasal volume by placing subjects in the supine position would increase the ability of the nose to warm and humidify air compared with unaltered nasal volume in the upright position.

Methods

Subjects. We recruited six healthy volunteers with no history of allergic rhinitis (5 men and 1 woman; ages 19 to 31 yr, mean, 24 yr). Their nonallergic status was confirmed by negative skin puncture testing with a panel of common allergens in the Chicago area. No subjects were taking medications within 2 wk of the evaluation, and none of them had other medical problems. The study was approved by the Institutional Review Board of the University of Chicago, and written informed consent was obtained from each subject before study entry.

Experimental protocol. We performed a randomized, two-way crossover study comparing the effects of placing subjects in the upright and supine position on the ability of the nose...
Nasal volume measurement

Blood pressure and pulse were measured. The volume of both nasal cavities was measured by acoustic rhinometry (see Nasal volume measurement). The more patent side was chosen for probe insertion because the less patent side has been shown to be affected most by postural change (10). Then, nasal mucosal temperature was measured (see Nasal mucosal temperature measurement) on the less patent side.

The more patent nostril was sprayed with three puffs (0.3 ml) of 0.05% oxymetazoline hydrochloride (Nostrilla, Ciba Self-Medication, Woodbridge, NJ), followed by three puffs (0.3 ml) of 4% topical lidocaine hydrochloride (Roxane Laboratories, Columbus, OH). Five minutes later, a probe containing a temperature sensor was inserted through the nose along the floor of the nasal cavity so that the tip touched the posterior nasopharyngeal wall, and the sensor was suspended in the airstream facing the opposite nostril. Flexible nasopharyngoscopy (Flex View Nasopharyngoscope, Smith and Nephew ENT, Bartlett, TN) was then performed to verify the position of the probe. The nostril containing the probe was then occluded anteriorly with a wax plug (Mack’s Earplug, McKeon Products, Pleasant Ridge, MI). After that, a second series of baseline measurements was obtained that included blood pressure, pulse, nasal volume, and nasal mucosal temperature on the less patent side (baseline 2 (B2)). Then, the measurement of nasal conditioning was begun (see Nasal conditioning measurement). At the end of CDA exposure, before removal of the mask, nasal mucosal temperature was measured in duplicate while the subjects were still wearing the mask. After that, the mask was removed, and measurements of blood pressure, pulse, nasal volume, and nasal mucosal temperature were repeated [after first CDA exposure (AC1)]. The probe was left in the nasal cavity, and nasal volume measurement was performed on the other side every 5 min until the volume returned to the baseline value (B1). Preliminary experiments showed that nasal volume returned to baseline within ~30 min. After that, nasal conditioning measurement in the other position was begun. The supine position was achieved by using an ear, nose, and throat chair (Reliance Medical Products, Cincinnati, OH).

The above processes were repeated again [baseline 3 (B3), after second CDA exposure (AC2)] (Fig. 1). On the other visit, the order of positions during nasal conditioning measurement was reversed. For example, if the first visit was upright followed by supine position, the second visit would start with supine followed by upright position.

Nasal conditioning measurement. The technique to evaluate the ability of the nose to condition CDA has been described in detail previously (31). In brief, a nasal continuous positive airway pressure mask (Respironics, Murrysville, PA) was applied to the face over the probe with head straps. The first probe containing a temperature sensor was inserted into the nasopharynx, and a second probe containing another temperature sensor was inserted into the mask and positioned just outside the nasal cavity. Silicone wax was used to provide an airtight seal around the probes where they entered the mask. Relative humidity (RH) was assumed to be 0% in the mask during CDA exposure and to be 100% in the nasopharynx. This assumption is based on the data from our laboratory’s prior study (31).

Air from compressed air tanks (Gas Tech, Hillside, IL) was passed through a flowmeter into a cold-air machine (FTS Systems, Stone Bridge, NY). Cold air at 0% RH was then delivered to the patient’s nose via the mask at flow rates of 5, 10, and 20 l/min. The air temperature was ~19, 10.5, and 0.8°C at 5, 10, and 20 l/min, respectively. The subjects were instructed to breathe in and out through the mouth. Exposure to each flow rate lasted 12 min. The last 5 min at each flow rate were used to calculate the water content of the air by the standard formula (31). The difference between the water content of air before entry into the nose and that in the nasopharynx is the water gradient (WG) across the nose, which represents the amount of water evaporated by the nose to condition air.

Nasal mucosal temperature measurement. A nasal probe was used to measure mucosal surface temperature as previously described (2). The temperature sensor at the end was placed in contact with the nasal mucosa of the anterior part of nasal septum just posterior to the mucocutaneous junction, and the sensor sampled the mucosal temperature at a rate of 1 measurement per second for 30 s. The mean of the collected data during this period is reported. Measurement of nasal mucosal temperature during CDA exposure was performed by advancing the temperature sensor through a small opening in the mask. When the temperature sensor was in the airstream, there was fluctuation of the tracing, which was lost with a sudden change in temperature when the probe contacted the nasal septal mucosa. The nasal mucosal temperature during CDA exposure was measured twice and

![Fig. 1. Protocol. Different interventions, including measurements of blood pressure (BP), pulse (P), nasal volume (VOL), nasal mucosal temperature (NMT), drug administration, and probe insertion, are depicted by arrows. Intervals are not shown on a time scale but are simply arranged in the order that they were performed. Baseline 1 (B1) and baseline 2 (B2) are 5 min, whereas each cold, dry air (CDA) exposure is 32 min. Dotted vertical line indicates separation between nasal conditioning measurement in each position. During this time interval, nasal volume measurement was performed on the less patent nostril every 5 min until the volume returned to the baseline value before the other nasal conditioning measurement was made, usually within 30 min. Placement of subjects in the supine position occurred before B2 or baseline 3 (B3) time points, depending on randomization code. Nasal mucosal temperature during CDA exposure was measured at the end of CDA exposure at the flow rate of 20 l/min. AC1 and AC2, after first and second CDA exposure, respectively. Procedure was performed on the less patent nostril. Procedure was performed on the more patent nostril.](http://jap.physiology.org/doi/10.12324/jap200101)
Nasal volume measurement. Nasal volume measurement was performed with an Eccovision Acoustic Rhinometry System (Hood Laboratories, Pembroke, MA). The volume was measured at 2–6 cm from the tip of the rhinometry probe. Each measurement was performed in triplicate, and the average values are reported. The accuracy of the acoustic measurements has been verified in models of the nasal cavity (18). In addition, human experimentation has shown the predicted effect of decongestants (12, 40). The measurements have also been compared with magnetic resonance imaging and computed tomography scans of the nasal cavity with good accuracy (12, 18). Nasal volume measurements cannot be made while subjects are wearing the mask to deliver CDA.

Statistical analysis. For the WG, statistical analysis was performed by using parametric statistics. This choice is based on the normal distribution of data (31). Total WG was calculated as the sum of the nasal WG during each of three flow rates tested (5, 10, and 20 l/min). Repeated measurements of WG were compared by ANOVA, and post hoc analysis was performed with Fisher’s test of least significant difference. Comparison of WG among three flow rates within each position was done by paired t-test. To study the effect of postural change on nasal conditioning capacity, we compared total WG values and WG at each flow rate obtained with the subjects in the upright and supine positions by using the paired t-test. We also studied the reproducibility of the response to CDA by comparing total WG obtained from each position between first and second visits using paired t-test.

For other parameters, nonparametric statistics were used for analysis because the data were not normally distributed. Repeated measurements within each position were first analyzed by Friedman ANOVA, and, if a significant difference was found, post hoc analysis between two selected time points was performed by using the Wilcoxon signed-rank test. The percentages of CDA-induced change of nasal volume and nasal mucosal temperature from baseline [nasal volume: (AC1 – B2)/B2 × 100 or (AC2 – B3)/B3 × 100, nasal mucosal temperature: [temperature during CDA exposure – B2 or B3]/B2 or B3 × 100] were also calculated and compared between both positions using the Wilcoxon signed-rank test.

Correlations were performed by the Spearman rank method. A P value (2-tailed) < 0.05 was considered to indicate significance. WG values are presented as means ± SE. Other parameters are presented as median, with the 25th–75th percentiles in parentheses.

RESULTS

In both positions, increasing the CDA flow rate progressively increased the WG (Fig. 2). In the supine position, WG values obtained at all flow rates (P < 0.01) as well as the total WG (P < 0.001) were less than those obtained in upright position (Fig. 2). For all flow rates, the WG per one volume unit of air was still significantly less in supine position compared with upright position (Table 1).

The reproducibility of total WG in each position was studied by comparing total WG between the first and second visits. In both positions, the mean total WG values obtained from both visits were not statistically different (upright: P = 0.3, supine: P = 0.4, both positions: P = 0.2). The coefficient of variation (%) (SD/mean × 100%) of total WG obtained during both visits ranged between 0 and 19.7% and averaged 9.4% in upright position, and it ranged between 3.4 and 28.8% and averaged 18.5% in supine position. Within each position, increasing the CDA flow rate progressively decreased the WG per unit of air, regardless of position (ANOVA: upright: P = 0.2, supine: P = 0.2) (Table 1).

When subjects were placed in the supine position, the nasal volume decreased significantly compared with that in the upright position (P < 0.01) (Fig. 3). After nasal conditioning measurement, nasal volume decreased significantly in both positions, and the nasal volume after CDA exposure in the supine position was significantly less than that in the upright position (P < 0.05). However, there were no significant differences in net change of CDA-induced decrease in nasal volume between both positions (Fig. 3).

The nasal mucosal temperature in the supine position was not significantly different compared with that in the upright position at baseline (Fig. 4). There were statistically significant decreases in nasal mucosal
The nasal mucosal temperature during CDA exposure in both positions. The nasal mucosal temperature during CDA exposure in the supine position was significantly less than that in the upright position ($P < 0.01$) (Fig. 4). Furthermore, the magnitude of the reduction in nasal mucosal temperature was significantly greater during the supine position compared with the upright position (Fig. 4). After removal of the mask, nasal mucosal temperature returns almost instantaneously to baseline levels.

There were no significant differences in systolic, diastolic, and mean arterial blood pressure or in pulse before, during, and after CDA exposure in both positions (Table 2). However, pulse before (60 vs. 58 beats/min; $P < 0.05$) and during (60 vs. 57 beats/min; $P < 0.05$) CDA exposure in the supine position was significantly less than those values in the upright position. There were no significant correlations between nasal volume, nasal mucosal temperature, pulse, or blood pressure and total WG. Pulse and blood pressure did not change significantly between the two positions.

### Table 1. Comparison of water gradient in upright and supine positions

<table>
<thead>
<tr>
<th>Flow Rate</th>
<th>Upright</th>
<th>Supine</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 l/min</td>
<td>90.1 ± 6.5</td>
<td>72.2 ± 6.3*</td>
</tr>
<tr>
<td>10 l/min</td>
<td>163.0 ± 14.4</td>
<td>124.2 ± 11.9*</td>
</tr>
<tr>
<td>20 l/min</td>
<td>287.3 ± 29.3</td>
<td>222.9 ± 24.5*</td>
</tr>
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</table>

Values are means ± SE for 6 subjects with 12 nasal conditioning measurements in each position. WG, water gradient. *$P < 0.01$ vs. respective flow rate of upright position.
Our laboratory’s results showed that subjects had previously responded to our laboratory’s clinical sensitivity to cold, windy environments. All et al., we selected 10 subjects who gave a history of the nose for 45 min during two separate

**DISCUSSION**

According to a theoretical model of localized heat and water vapor transport in the nose, the two most important parameters predicting the air-conditioning process are nasal mucosal temperature and volume of the nasal cavity (16). We reduced the nasal volume without altering the mucosal temperature by placing subjects in the supine position and studied this effect on nasal conditioning capacity. Contrary to the theoretical model, in the supine position, subjects were less able to condition CDA compared with the upright position, demonstrating the need to test models with human data. The simple prediction must not have accounted for the complexity of the human situations.

We chose to evaluate unidirectional rather than bidirectional breathing for both practical and theoretical reasons. In the past, when our laboratory used the inhalation of CDA as a stimulus to induce inflammation, there was criticism about the use of a unilateral stimulus because it ignored the water that is recovered during expiration (38). Strohl and colleagues (35) showed that the inhalation of air in through the nose and out through the mouth induced an increase in nasal airway resistance, but when the same subjects inhaled and exhaled air through the nose, their airway resistance did not increase. They interpreted their experiment to imply that the pattern of breathing influences the response and that the recovery of heat during expiration prevents the response. Superficially, this work appeared to negate our laboratory’s previous studies (38). To show that the nasal mucosa does respond to CDA when inhaling and exhaling air through the nose, our laboratory performed experiments designed to address this issue (26). In contrast to Strohl et al., we selected 10 subjects who gave a history of clinical sensitivity to cold, windy environments. All subjects had previously responded to our laboratory’s standard CDA challenge. The subjects were randomized to breathe either CDA or warm, moist air in and out through the nose for 45 min during two separate visits. Our laboratory’s results showed that subjects had significant increases in nasal secretion weight as well as vascular permeability markers and histamine levels after CDA compared with warm, moist air provocation (26). Although significantly increased, these levels did not change to the extent of those reported previously (38). This difference was anticipated on the basis of the reduction of the stimulus, the amount of air to be conditioned. The fact that there was a significant change implies that the nasal mucosa does respond to conditioning CDA even though there is an estimated 30% recovery during exhalation. We believe that our laboratory’s protocol to breathe in through the nose and out through the mouth represented a means to augment the stimulus so that it was easier to study. An analogy is that the inhalation of air with 5% CO2 in a volume of 140 liters through the mouth while seated wearing nose clips serves as a model of exercise-induced asthma (15).

In the experiments reported here, we were concerned about the instrumentation. The exhalation of 100% RH air would lead to condensation on the probe in the nasopharynx, probably interfering with the accuracy of the measurements. Steady-state conditions are also necessary to achieve accurate readings because there are a number of potential heat sinks within the nose, within the probe, and within the delivery system. This is why the initial recordings from the probe are disregarded (31). Finally, it is the air exiting the nose into the nasopharynx that will be responsible for shifting conditioning to the lower airway.

The nasal mucosa contains 1) resistance vessels, which control the blood flow to the mucosa; 2) exchange capillaries, which are responsible for filtration and absorption of fluid; 3) capacitance vessels, which are responsible for blood volume; and 4) arteriovenous or shunt vessels (23). Nasal airway resistance is mainly determined by the degree of engorgement of the capacitance vessels or venous sinuses in the nasal mucosa. Nasal venous sinuses are sensitive to changes in venous pressure caused by changes in posture (14, 17, 20, 32). Our data showed that placing subjects in the supine position decreased nasal air volume significantly.

The techniques for measuring nasal blood flow in humans have been limited to laser-Doppler flowmetry and Xenon clearance. Xenon clearance is less in the

| Table 2. Comparison of systolic, diastolic, and mean arterial blood pressure and pulse before, during, and after CDA exposure |

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Upright Before CDA</th>
<th>During CDA</th>
<th>After CDA</th>
<th>Supine Before CDA</th>
<th>During CDA</th>
<th>After CDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systolic blood pressure, mmHg</td>
<td>115 (108–120)</td>
<td>110 (110–120)</td>
<td>110 (108–120)</td>
<td>110 (108–120)</td>
<td>110 (110–120)</td>
<td></td>
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<tr>
<td>Diastolic blood pressure, mmHg</td>
<td>80 (70–80)</td>
<td>80 (78–80)</td>
<td>75 (70–80)</td>
<td>70 (70–80)</td>
<td>80 (70–80)</td>
<td></td>
</tr>
<tr>
<td>Mean arterial blood pressure, mmHg</td>
<td>90 (86–92)</td>
<td>90 (86–93)</td>
<td>87 (82–93)</td>
<td>87 (83–90)</td>
<td>90 (83–93)</td>
<td></td>
</tr>
<tr>
<td>Pulse, beats/min</td>
<td>61 (56–68)</td>
<td>60 (58–64)</td>
<td>60 (59–64)</td>
<td>58* (56–60)</td>
<td>57* (56–60)</td>
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Values are medians of 12 observations with 25th–75th percentiles in parentheses. *P < 0.05 vs. respective upright.
sitting position compared with the supine position (4), whereas nasal mucosal blood content is increased in the supine position. In contrast, laser-Doppler flowmetry showed no changes in capillary blood flow in the supine compared with the upright position (28). Cold-room exposure decreased both xenon clearance and nasal patency (27). Laser-Doppler flowmetry also decreased with the placement of feet in cold water (28). Exercise in the supine position led to an increase in nasal patency but no change in xenon clearance (29). Unfortunately, techniques to measure blood flow in humans leave room for improvement, but it is clear that the various components of the nasal mucosal blood flow can operate independently. In the large airways of the lung, by using the technique of diethyl ether uptake, hyperventilation with frigid air, in contrast to room air, caused an increase in blood flow (21, 41).

In our study, nasal volume decreased significantly after CDA exposure in both positions, consistent with previous reports (11, 13, 33). Velocity of air is inversely proportional to the cross-sectional area (36). With the fixed amount of air that was blown into a nasal cavity with decreased volume and cross-sectional area in the supine position the pressure and velocity of air in the nasal cavity would be higher in the supine position, compared with the upright position. Theoretically, the increased velocity of air would result in more turbulence of airflow, more intimate mucosal contact and mixing, and more water evaporation (10). However, increasing the velocity of air could also result in less water evaporation per unit volume of air because less time was available for the mucosa to contact air, as demonstrated in Table 1. Moreover, increased air speed induced by sniffing has been shown to decrease the temperature and relative humidity of air in the nasopharynx (31). Because the amount of water evaporated from the nose to condition air is a function of the temperature and humidity of air (31), the decrease in nasal air temperature induced by increased air speed would decrease the amount of water evaporated from the nasal mucosa. Because the subepithelial network of fenestrated capillaries is a major source of fluid for humidification and heat for the mucosal surface (6, 7), elevated pressure in the airstream could reduce blood flow through this subepithelial superficial capillary network. These changes would lead to decreased ability to condition air in the supine position and would explain our results.

Our results demonstrated that nasal mucosal temperature decreased significantly during inhalation of CDA in both positions, consistent with previous observations (3, 9). Nasal mucosal temperature was significantly less at the end of exposure, and the magnitude of CDA-induced reduction in nasal mucosal temperature was greater in the supine position, compared with the upright position. The mechanism underlying such a decrease is unknown. There was a significant decrease in pulse, although not in blood pressure, in the supine position, compared with the upright position. The decrease in pulse may imply lower cardiac output (5) and less blood flow to the nasal mucosa in the supine position. Furthermore, increased pressure in the airstream in the supine position possibly reduced subepithelial superficial capillary blood flow and led to decreased heat brought to the surface and a more accentuated decrease in nasal mucosal temperature. Moreover, the increased filling pressure of the venous sinuses induced by placing subjects in the supine position might create negative backpressure to resistance vessels and probably decreased blood flow to those vessels. Taken together, these events might lead to a reduction in nasal mucosal blood flow and nasal mucosal temperature in the supine position. Because, according to the law of conservation of matter and energy, total heat and water received by the air is equal to the loss from the nasal mucosa-blood interface (36), a decreased nasal mucosal temperature is probably responsible for the lower amount of water evaporated in response to CDA exposure in the supine position.

The dissociation between nasal mucosal temperature and nasal volume during changes in posture is consistent with previous work (22), emphasizing that vessels in different parts of the nasal mucosa respond differently to the same stimulus. Unfortunately, we cannot directly measure blood flow in the different compartments of the nose to support our conclusions further.

Nocturnal worsening of arterial saturation, which appeared to be a body position-related phenomenon, has been reported in patients with congenital heart disease and Eisenmenger’s syndrome (34). Alveolar oxygen pressure and oxygen saturation were significantly decreased in the supine position compared with the sitting position. Because both of these parameters could be corrected with nasal oxygen, a ventilation-perfusion distribution abnormality and/or a diffusion limitation phenomenon rather than an increase in true shunt may be the mechanisms responsible for this finding. Because the nose is the main air conditioner of the respiratory system, its dysfunction may negatively affect the lower airways. In the supine position, the decrease in the ability to condition air in the upper airway may, at least partially, lead to an abnormality in the lower airway. The reduced ability to condition air, which may lead to decreased air temperature in the lower airway, when subjects are in the supine position, could be a potential mechanism of nocturnal asthma (24). In support of this statement, blocking the temperature drop in asthmatic subjects by breathing warm, humidified air (37°C and 100% RH) improved the overnight decrement in lung function and oral temperature (8).

In summary, we have shown that subjects in the supine position demonstrate a reduced ability of the nose to condition air. The precise mechanism remains to be established.

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REFERENCES
NASAL CONDITIONING DECREASES DURING RECUMBENCY


