The principle of upper airway unidirectional flow facilitates breathing in humans

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Submitted 1 May 2008; accepted in final form 29 June 2008

Jiang Y, Liang Y, Kacmarek RM. The principle of upper airway unidirectional flow facilitates breathing in humans. J Appl Physiol 105: 854–858, 2008. First published July 3, 2008; doi:10.1152/japplphysiol.90599.2008.—Upper airway unidirectional breathing, nose in and mouth out, is used by panting dogs to facilitate heat removal via water evaporation from the respiratory system. Why some humans instinctively employ the same breathing pattern during respiratory distress is still open to question. We hypothesized that 1) humans unconsciously perform unidirectional breathing because it improves breathing efficiency, 2) such an improvement is achieved by bypassing upper airway dead space, and 3) the magnitude of the improvement is inversely proportional to the tidal volume. Four breathing patterns were performed in random order in 10 healthy volunteers first with normal breathing effort, then with variable tidal volumes: mouth in and mouth out (MMB); nose in and nose out (NMB); nose in and mouth out (NMB); and mouth in and nose out (MBN). We found that unidirectional breathing bypasses anatomical dead space and improves breathing efficiency. At tidal volumes of ~380 ml, the functional anatomical dead space during NMB (81 ± 31 ml) or NBM (101 ± 20 ml) was significantly lower than that during MMB (148 ± 15 ml) or NNMB (130 ± 13 ml) (all P < 0.001), and the breathing efficiency obtained with NMB (78 ± 9%) or NNB (73 ± 6%) was significantly higher than that with MMB (61 ± 6%) or NNMB (66 ± 3%) (all P < 0.001). The improvement in breathing efficiency increased as tidal volume decreased. Unidirectional breathing results in a significant reduction in functional anatomical dead space and improvement in breathing efficiency. We suggest this may be the reason that such a breathing pattern is preferred during respiratory distress.

pursed lip breathing; breathing efficiency; anatomical dead space; respiratory failure; panting

DOGS DISSIPATE EXCESS HEAT mainly by panting through the removal of water vapor via the respiratory system (2). Although there are several patterns of panting, which is rapid breathing with small tidal volumes, unidirectional flow panting, nose in and mouth out has been shown to be the most efficient (17). This is because unidirectional flow panting avoids the water vapor recycling that normally occurs in the upper airway during bidirectional panting, nose in and nose out, or mouth in and mouth out (17).

The mechanism of CO2 removal in humans shares similarities with that of water vapor removal in panting dogs. When humans perform bidirectional nasal breathing, nose in and nose out, at end exhalation the entire airway is filled with CO2-containing gas. As a result, during the subsequent inspiration, CO2-containing gas in the airway enters alveoli before fresh gas. Thus some CO2 is recycled just as water vapor is recycled during bidirectional panting in dogs. Therefore, breathing efficiency, defined as the volume of fresh gas reaching alveoli (alveolar tidal volume) divided by the total volume of the gas inhaled per breath (total tidal volume), is only ~60–70% for normal adults at rest (10). Approximately 30–40% of inhaled fresh gas does not reach the alveoli, which is referred to as dead space (wasted) ventilation.

Individuals with compromised respiratory function breathe shallowly and rapidly (5). With a small tidal volume, the fraction of dead space ventilation increases and may reach >50% (4). As a result, breathing efficiency further decreases. Interestingly, some humans instinctively apply upper airway unidirectional breathing, nose in and mouth out, during respiratory distress, just like panting dogs during heat overload (6). This breathing pattern is referred to as pursed-lip breathing and is frequently observed in patients with chronic lung or neuromuscular diseases (6, 20–22). Although pursed-lip breathing has been described and recommended for use by patients for over five decades, little is known about why it is a preferred breathing pattern during respiratory distress. It has been believed that the expiratory resistance induced by pursed lip breathing stabilizes the bronchial tree, reduces airway collapse and air trapping, and facilitates exhalation (16). However, this explanation has been questioned (9). Furthermore, such a breathing pattern has also been observed in patients with respiratory muscle dysfunction (21). In such patients with normal lungs, increases in expiratory resistance should not lead to improvements in breathing. We hypothesized that 1) humans unconsciously perform unidirectional breathing because it improves breathing efficiency, 2) the improvement in breathing efficiency is a result of a bypass of upper airway dead space, and 3) the magnitude of the improvement in breathing efficiency is inversely proportional to the tidal volume. We tested our hypothesis in healthy volunteers.

MATERIALS AND METHODS

The study was approved by the Massachusetts General Hospital Human Research Committee (Boston, MA), and written, informed consent was obtained from all subjects.

Subjects. A total of 11 healthy volunteers over 18 yr of age were recruited. We ensured that, at rest, all subjects were able to breathe through both their nose and mouth without using respiratory accessory muscles. Exclusion criteria included 1) facial deformity, heavy beard or moustache, which prevented a good mask seal; and 2) subjects with claustrophobia who could not wear the mask.

Study design. A combined nasal-oral mask was applied to the subject’s face (Fig. 1). This mask was composed of a nasal mask (Vinyl Nasal Disposable Mask, Respiromics, Murrysville, PA) and an oral piece (Oracle 452 Oral CPAP/BiPAP Mask, Fisher & Paykel

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after the subject had reached a stable breathing pattern and the
to baseline. For each breathing pattern, measurements only began
by occluding the nasal mask or mouth piece and removing the one-way
Breathing parameters were recorded with a NICO monitor (NICO,
Wallingford, CT) was placed in the exhalation limb of the mask.
Respiratory parameters were recorded with a NICO monitor (NICO,
Noninvasive Cardiopulmonary Management System, model 7300,
Respirronics) connected to the sensor.

Subjects were first instructed to perform in a random order the four
breathing patterns (NNB, MMB, NMB, and MNB) at a normal
ventilation increased, and the improvement in breathing effi-
cuency by reduction of Vdan became even more profound.

As tidal volume decreased, the fraction of the dead space
ventilation increased, and the improvement in breathing effi-
ciency by reduction of Vdan became even more profound.

Subjects were first instructed to perform in a random order the four
breathing patterns (NNB, MMB, NMB, and MNB) at a normal
breathing effort. Each breathing pattern was performed for 5 min (3
min of stabilization and 2 min of data collection), and the last 10
breaths were used for data analysis. Subjects rested for at least 10 min
between each breathing pattern to allow their end-tidal PCO2 to return
Healthcare, Parnure, Auckland, New Zealand). Each piece contained a
one-way valve directing flow. By adjustment of the direction of the
one-way valves or their occlusion, nose-in nose-out breathing (NNB),
mouth-in mouth-out breathing (MMB), mouth-in nose-out breathing
(MNB), and nose-in mouth-out breathing (NMB) was achieved. The
mask was secured by head straps, and air leaks were minimized by
appropriate mask size. The seal on the masks was checked by asking
the subject to forcefully exhale against an occluded mask generating
at least 30-cmH2O airway pressure and visually inspecting and pal-
pating to ensure that there was no air leak discernible to the subject or
investigators.

A mainstream flow sensor and infrared carbon dioxide analyzer
(Adult Combined CO2/Flow Sensor, Novametrix Medical Systems,
Wallingford, CT) was placed in the exhalation limb of the mask.

Subjects were first instructed to perform in a random order the four
breathing patterns (NNB, MMB, NMB, and MNB) at a normal
breathing effort. Each breathing pattern was performed for 5 min (3
min of stabilization and 2 min of data collection), and the last 10
breaths were used for data analysis. Subjects rested for at least 10 min
between each breathing pattern to allow their end-tidal PCO2 to return
to baseline. For each breathing pattern, measurements only began
after the subject had reached a stable breathing pattern and the
individual’s end-tidal PCO2 did not vary $>2$ Torr. To minimize the
influence of head position on anatomical dead space (Vdan), all
subjects sat upright and were instructed to hold their head erect.

To determine the influence of tidal volume on breathing efficiency,
in the second experiment, subjects were instructed to breath in
slowly, then to progressively increase tidal volume to near max-
imum capacity, and then to decrease tidal volume to their starting
level. This maneuver was randomly repeated with each of the four
breathing patterns.

Data analysis. The Vdan was calculated as $V_{\text{dan}} = V_{\text{Te}} \times \left(1 - \frac{MCO_2}{ETCO_2}\right)$, where $V_{\text{Te}}$, $MCO_2$, and $ETCO_2$ represent exhaled

RESULTS

A total of 11 subjects were enrolled. One subject was
excluded because of an inability to achieve an adequate mask
seal. As a result, 10 subjects completed the protocol. The
subjects were five males and five females, age $40 \pm 11$ yr,
height $171 \pm 9$ cm, and weight $73 \pm 16$ kg.

Since Vdan is affected by tidal volume (18), the compar-
ison of Vdan among the four breathing patterns was per-
formed at similar tidal volumes. We found that unidirec-
tional breathing (NMB and MNB) significantly reduced
functional Vdan and improved breathing efficiency com-
pared with bidirectional breathing (NNB and MMB) at
similar tidal volume and end-tidal CO2 level (Fig. 2).
Significant differences in functional Vdan were also ob-
erved among the four breathing patterns (Fig. 2). However,
the greatest reduction (74 ml; $P < 0.001$) in functional Vdan
occurred when MMB (189 $\pm$ 39 ml) was compared with
NMB (115 $\pm$ 39 ml). The second greatest difference (51 ml;
$P < 0.001$) in functional Vdan was found between NNB
(166 $\pm$ 34 ml) and NMB (115 $\pm$ 39 ml). MNB (146 $\pm$ 43
ml) also significantly reduced functional dead space com-
pared with NNB (166 $\pm$ 34 ml) or MMB (189 $\pm$ 39 ml).
However, many subjects reported difficulty and lack of
coordination performing MNB or developed a dry mouth
during MNB but not during NMB. As a result of the reduction
of MNB (78 $\pm$ 9%) or MMB (73 $\pm$ 6%) (all
$P < 0.001$) in functional Vdan, breathing efficiency during
MNB was 50% higher than that during MMB (61 $\pm$ 6%)
($P < 0.001$; Fig. 2A), and the breathing efficiency obtained with
NMB (78 $\pm$ 9%) or MNB (73 $\pm$ 6%) was significantly higher than that with MMB (61 $\pm$ 6%) or NNB (66 $\pm$ 3%)
($P < 0.001$; Fig. 2C). The greatest improvement (17.5%) in breath-
ing efficiency again occurred when MMB was compared with
NMB ($P < 0.001$). Furthermore, at a tidal volume close to 300
ml, the breathing efficiency during MMB was only 50%,
whereas the breathing efficiency during NMB was 70%.
relation of breathing efficiency to tidal volume can be expressed as the following:

**MMB:** Breathing efficiency $= 0.23 \cdot VTe^{0.17}$

**NNB:** Breathing efficiency $= 0.31 \cdot VTe^{0.13}$

**NMB:** Breathing efficiency $= 0.49 \cdot VTe^{0.08}$

**MNB:** Breathing efficiency $= 0.42 \cdot VTe^{0.09}$

**DISCUSSION**

The primary findings of this study are summarized as 1) upper airway unidirectional breathing significantly bypasses Vdan and improves breathing efficiency compared with bidirectional breathing and 2) the magnitude of improvement in breathing efficiency increases as tidal volume decreases.

The improvement in CO2 removal can be demonstrated by analysis of the CO2 expirogram (exhaled volume vs. exhaled CO2 fraction). Typical breaths with a tidal volume of ~600 ml obtained from a single subject are displayed in Fig. 4. During NMB and MNB, extra volumes of CO2-containing gas were exhaled compared with NNB and MMB. This is also illustrated in Fig. 5. The airway is filled with CO2-containing gas at end expiration during NNB (Fig. 5A). All the CO2-containing gas in the entire airway is inhaled and recycled during the subsequent inhalation. In contrast, the nasal and partial pharyngeal cavity is filled with fresh gas at end expiration during NMB (Fig. 5B). The fresh gas, instead of the CO2-containing gas, in the nasopharyngeal cavity is inhaled during the subsequent inhalation. The CO2-containing gas in the oral cavity (Fig. 5B) is not recycled into the lung since inhalation only occurs via the nasal cavity. Rather, this portion of CO2-containing gas is exhaled in the subsequent exhalation. Therefore, a large portion of CO2, which is normally recycled in upper airway bidirectional breathing, is not recycled when upper airway unidirectional breathing is employed.

Our study found that the greatest reduction (74 ml) in functional Vdan occurred when MMB was compared with NMB. By switching from MMB to NMB, the dead space of the oral cavity and partial pharyngeal cavity was bypassed. This reduction of 74 ml is approximately equal to the volume of the oral and pharyngeal cavity measured in human cadavers (72 ml) (3, 14). The second greatest difference (51 ml) in functional Vdan was found between NNB and NMB. The dead
space of the nasal cavity and partial, if not total, pharyngeal cavity during NMB were bypassed compared with NNB. The volume of the dead space bypassed by switching from NNB to NMB is again similar to that of the nasopharyngeal cavity (45 ml) (15).

Our study also demonstrated that MNB significantly reduces Vdan and improves breathing efficiency compared with NNB or MMB. However, MNB is not the preferred route of ventilation for the following reasons. First, inspired air is usually warmed and humidified in the nose but not in the mouth. Second, particle deposition is more efficient in the nasal than in the oral cavity. Third, NMB is the more natural way of breathing rather than MNB. In our study, most patients reported difficulty and lack of coordination performing MNB or developed a dry mouth during MNB but not during NMB.

The Vdan during NMB and MNB should be the same or at least similar. However, in this study, we found that Vdan during NMB (115 ml) was lower than MNB (146 ml). We believe that NMB and MNB generate different patterns of air turbulence, and the turbulence generated by NMB produces more Vdan reduction than that of MNB. A similar effect has also been observed during tracheal gas insufflation (12).

A reduction of 50–70 ml in Vdan may not seem significant. However, patients with respiratory disorders breathe with small tidal volumes. Since the fraction of dead space ventilation is inversely proportional to the tidal volume, breathing with a small tidal volume can result in dead space ventilation of greater than 50% of tidal volume (4). Thus even a small reduction in Vdan can produce a marked improvement in breathing efficiency. Studies on patients requiring mechanical ventilation indicate that removing 40 ml of mechanical dead space at a constant minute ventilation reduces the partial pressure of CO2 in arterial blood from 46 to 40 Torr (11). Tracheal gas insufflation of dogs resulting in only a 31-ml reduction in dead space leads to a fall in arterial CO2 partial pressure from 79 to 55 Torr (13). Tracheal gas insufflation in patients with severe ARDS produces a similar effect (1). Our results indicate that the reduction in Vdan with NMB is much larger than that obtained with tracheal gas insufflation. In addition, since patients with respiratory distress tend to breathe through a widely opened mouth, the dead space of the oral cavity under this situation would be even larger than that of our volunteers, and the benefit of upper airway unidirectional breathing may even be greater than that shown by our data.

Our study also found that the improvement of breathing efficiency increased, although Vdan decreased with decreasing tidal volume (Fig. 3). Studies have shown that Vdan decreases significantly with tidal volume (19), thus the percentage of Vdan will be larger and the improvement of breathing efficiency with upper airway unidirectional breathing will be more profound with smaller tidal volume. Therefore, application of this principle is most useful in patients breathing with small tidal volumes. This may also explain why unidirectional pursed-lip breathing is instinctively applied by patients who develop a rapid and shallow breathing pattern (6, 20–22).

Tracheotomy is another way to reduce dead space ventilation and improve the efficiency of ventilation. Studies have shown that tracheostomy can reduce Vdan by 70 ml and reduce work of breathing by over 30% (4). Even though it is invasive and associated with many complications, it has successfully been used to treat patients with respiratory failure mainly due to its reduction in Vdan (4, 7, 8). Our study demonstrates that simple upper airway unidirectional breathing, nose in and mouth out, achieves a similar degree of reduction in Vdan as tracheostomy without interruption of the integrity of the natural airway. We believe this breathing pattern would achieve a benefit similar to that of tracheostomy in terms of reduction in work of breathing, oxygen consumption, and may ultimately improve patient’s outcome.

The limitations of this study are as follows. First, this study was done in healthy volunteers, not in patients who might benefit from PLB. The lung physiology and mechanics of healthy volunteers are different from those of patients. However, since bypassing Vdan during upper airway unidirectional breathing only involves the upper airway, the benefit should be similar for both healthy volunteers and patients. Second, since this study was done on volunteers simulating pursed-lip breathing, the other benefits of PLB may have been overlooked. However, the aim of this study was only to determine the effect of unidirectional breathing on dead space reduction and breathing efficiency. Further study is needed to determine the benefit
of upper airway unidirectional breathing in various groups of patients.

In conclusion, upper airway unidirectional breathing results in a significant reduction in functional Vdan and improvement in breathing efficiency. This benefit increases as tidal volume decreases. We suggest this may be the reason that such a breathing pattern is preferred during respiratory distress.

GRANTS

This work has been supported in part by a Massachusetts Technology Transfer Center Investigation Award 2007 to Y. Jiang.

REFERENCES


