Sustained hyperoxia stabilizes breathing in healthy individuals during NREM sleep

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Submitted 27 April 2010; accepted in final form 18 August 2010

Chowdhuri S, Sinha P, Pranathiageswaran S, Badr MS. Sustained hyperoxia stabilizes breathing in healthy individuals during NREM sleep. J Appl Physiol 109: 1378–1383, 2010. First published August 19, 2010; doi:10.1152/japplphysiol.00453.2010.—The present study was designed to determine whether hyperoxia would lower the hypocapnic apneic threshold (AT) during non-rapid eye movement (NREM) sleep. Nasal noninvasive mechanical ventilation was used to induce hypocapnia and subsequent central apnea in healthy subjects during stable NREM sleep. Mechanical ventilation trials were conducted under normoxic (room air) and hyperoxic conditions (inspired P O2 > 250 Torr) in a random order. The CO2 reserve was defined as the minimal change in end-tidal PCO2 (PETCO2) between eupnea and hypocapnic central apnea. The PETCO2 of the apnea closest to eupnea was designated as the AT. The hypocapnic ventilatory response was calculated as the change in ventilation below eupnea for a given change in PETCO2. In nine participants, compared with room air, exposure to hyperoxia was associated with a significant decrease in eupnic PETCO2 (37.5 ± 0.6 vs. 41.1 ± 0.6 Torr, P = 0.001), widening of the CO2 reserve (−3.8 ± 0.8 vs. −2.0 ± 0.3 Torr, P = 0.03), and a subsequent decline in AT (33.3 ± 1.2 vs. 39.0 ± 0.7 Torr; P = 0.001). The hypocapnic ventilatory response was also decreased with hyperoxia. In conclusion, 1) hyperoxia was associated with a decreased AT and an increase in the magnitude of hypocapnia required for the development of central apnea. 2) Thus hyperoxia may mitigate the effects of hypocapnia on ventilatory motor output by lowering the hypocapnic ventilatory response and lowering the resting eupnic PETCO2, thereby decreasing plant gain.

HYPOXIA PROMOTES BREATHING instability during sleep by increasing the susceptibility to develop hypocapnic central apnea and periodic breathing (7, 44, 46). Similarly, episodic hypoxia increases the propensity to develop central apnea, even after the removal of the hypoxic stimulus (7). Conversely, supplemental oxygen, used as a pharmacological agent, may stabilize respiration and has been shown to reduce the frequency of central apnea in patients with heart failure (33, 39). Acute hypoxia decreased the number of apneas and percent apnea time, although the result was inconsistent (25). The effect of hypoxia on ventilation is likely biphasic, manifesting as initial hypoventilation (12), secondary to the inhibition of peripheral chemoreceptors, followed by gradual hyperpnea (4, 5, 20, 35, 40, 42).

Brief hyperoxic exposure (Hyp) may also promote breathing stability during sleep. Xie et al. (46) demonstrated that brief Hyp was associated with reduced hypocapnic ventilatory response, owing to inhibition of peripheral chemosensitivity. Likewise, Wellman et al. (43) demonstrated that supplemental oxygen therapy reduced “loop” gain in patients with obstructive sleep apnea with high-loop gain, but not in those with low-loop gain. The mechanisms underlying the stabilizing effect of hyperoxia on ventilatory control during sleep remain uncertain. Therefore, the purpose of our study was to determine the physiological effect of sustained hyperoxia on the hypocapnic apneic threshold (AT) during non-rapid eye movement (NREM) sleep. We hypothesized that hyperoxia lowers the AT during NREM sleep in healthy individuals by increasing the carbon dioxide reserve.

METHODS

Participants

The Human Investigation Committees of Wayne State University School of Medicine and Detroit Veterans Affairs Medical Center approved the experimental protocols, and informed, written consent was obtained from all participants. All participants were nonsmoker healthy participants, nonsnorers, free of daytime sleepiness, and free from cardiovascular, pulmonary, neurological, or other medical disorders.

Breathing Circuit

Each participant was connected to the breathing circuit via a nasal mask. An appropriate-sized, airtight silicone nasal mask (Respironics, Murrysville, PA) was glued to the face to prevent mask leaks. The mask was connected to a Plateau Exhalation Valve (Respironics, Pittsburgh, PA), via a heated pneumotachometer. The valve, which provides a continuous leak path in the breathing circuit and serves as an exhaust vent, was connected to the inspiratory line. Participants were restricted to nasal breathing by placing tape over the mouth. During the mechanical ventilation (MV), protocol hyperventilation was achieved using a pressure support ventilator [bilevel positive airway pressure (PAP) machine; Resmed Sullivan VPAP II ST-A] for which the minimum allowable continuous PAP was 2 cmH2O. Gases were introduced from external sources connected to the inspiratory line. During the Hyp, participants breathed inspired O2 fraction (FIO2) of >35% from a 100% FIO2 gas source connected to the inspiratory line to keep inspired P O2 (PIO2) ≥ 250 Torr, whereas, during sham exposure (sham), participants breathed only room air introduced into the inspiratory line from a separate source.

Measurements

Electroencephalograms, electrooculograms, and chin electromyograms were recorded using the International 10–20 system of electrode placement (electroencephalogram: C3-A2 and C4-A1; electrooculogram, O-A2). Inspiratory airflow was measured by a heated pneumotachometer (model 3700A, Hans Rudolph, Kansas City, MO) attached to a RSS 100 HR Research Pneumotach System. The tidal volume (Vt) was obtained from the electronic integration of the flow
signal on the pneumotach system. To confirm the central etiology of
apnea and to ascertain upper airway mechanics, supraglottic pressure
was measured using a pressure transducer tipped catheter (model
TC-500XG, Millar Instruments, Houston, TX), with the tip positioned
in the hypopharynx. The hypopharyngeal position was obtained by
advancing the catheter tip for 2 cm after it disappeared behind the
tongue. End-tidal PCO2 (PETCO2) readings were obtained continuously
by an infrared analyzer (model CD-3A, AEI Technologies, Pittsburgh,
PA) from tubing placed in the nares via a port in the nasal mask.
Arterial O2 saturation (SaO2) was measured by a pulse oximeter (Biox
PA) from tubing placed in the nares via a port in the nasal mask.
Oxygen, while the PIO2 was continuously monitored to keep PIO2
constant during sleep. During Hyp, MV was conducted with continuous flow of
room air, as long as the MV protocol duration was not exceeded.
All trials were conducted while they were in stable stage 2 or stage 3
sleep on the first night repeated their respective experimental
protocol that was conducted during stable NREM sleep; hence,
participants assumed the supine position for the entire experi-
ment on the second night under the alternate condition, Hyp or sham, in the nine
participants.

Experimental Protocol

Overview. Hyperventilation via nasal MV was induced under
conditions of Hyp or sham in random order in nine participants.
Simple randomization was performed using a random table; the
participants were blinded to the order of condition. Study participants
were instructed to limit total sleep time to a maximum of 5 h on the
night preceding the study. Two participants who did not maintain
stable sleep on the first night repeated their respective experimental
studies with zolpidem 5 mg before the study, to allow uninterrupted
sleep. Participants assumed the supine position for the entire experi-
mental protocol that was conducted during stable NREM sleep; hence,
all trials were conducted while they were in stable stage 2 or stage 3
sleep. During Hyp, MV was conducted with continuous flow of
oxygen, while the PO2, was continuously monitored to keep PO2, ≥
250 Torr (see above). During sham, MV was conducted under room-
air conditions with bias flow of room air. One additional participant
also underwent sustained hyperoxia exposure, but could not complete
the MV protocol due to inability to maintain sleep during MV. Thus
10 participants were included in the “Sustained Hyperoxia” analysis,
while 9 were included in the “MV Protocol” analysis.

MV protocol. We used nasal noninvasive positive pressure MV to
produce hyperventilation to induce hyperventilation. This methodol-
gy has been previously described (7, 31, 32, 47). MV was applied for
3 min in the spontaneous–timed mode. In this mode, a backup
respiratory rate is preset; timed breaths are delivered, if the partici-
 pant’s rate falls below the backup rate (5–8 breaths/min). The venti-
lator respiratory rate was set at 5–8 breaths/min, which was below the
participant’s eupneic rate, to prevent neuromechanical inhibition of
ventilatory motor output (24). During MV, the inspiratory PAP was
increased gradually in 1- to 2-cmH2O increments, starting from 2
cmH2O at the beginning of each MV trial, while keeping expiratory
PAP fixed at 2 cmH2O throughout MV. MV was terminated after 3
min by returning the inspiratory PAP to the baseline expiratory PAP
of 2 cmH2O. The ensuing hypocapnia resulted in either a hypopnea or
central apnea. If an apnea was not induced, hyperventilation trials
were repeated until apnea was induced. Central apnea was defined as
an expiratory time ≥5 s. This methodology has been previously
described (7, 31, 32, 47). A compressed polygraph segment, obtained
from a participant in stage 2 sleep, before and during sustained
hyperoxia, is shown in Fig. 1. The MV protocol was repeated on a
second night under the alternate condition, Hyp or sham, in the nine
participants.

Data Analysis

Sustained hyperoxia before MV. Data recorded during exposure to
hyperoxia in the 10 participants before MV was used for analysis only
if it was measured during stable NREM sleep. Inspired VT, inspiration
time, total breath time, breathing frequency, minute ventilation (Vi),
PETCO2, inspired end-tidal PO2, SaO2, supraglottic pressure, and upper
airway resistance (RUA) were calculated breath by breath. RUA was
computed using pressure-flow loops plotted for every breath; this
methodology has been described previously (6, 34). For each variable,
an average value was computed during the control room air period
and during later hyperoxia period (sustained hyperoxia), just before the
onset of MV protocol. The variables outlined above were averaged
using 14 ± 4 (mean ± SD) breaths during control room air and using
5 breaths just before the onset of MV protocol (sustained hyperoxia,
Table 1).

MV protocol. Sleep staging (1) and scoring of arousals (38) was
completed using standard criteria, analyzing trials with stable NREM
sleep. We analyzed MV trials accompanied by a stable stage N2 or N3
sleep state for both Hyp and sham conditions. During the control
period, five breaths recorded immediately at the onset of MV were
averaged. Likewise, during the MV period, the last five mechanically
ventilated breaths before the return to baseline expiratory PAP were
averaged. The data analysis methodology has been previously de-
scribed (7, 31, 32, 47). The AT was defined as the PETCO2 that
demarcated the central apnea closest to the eupneic PETCO2. The CO2
reserve was defined as the change in PETCO2 between eupneic PETCO2
(control) and AT PETCO2 (ΔPETCO2). In addition, “hypocapnic venti-
latory response” was defined as the change in Vt between control and

![Fig. 1. Representative compressed polygraph segments from one participant. Compressed polygraph during non-rapid eye movement (NREM) sleep shows hyperventilatory period (x) in response to sustained hyperoxia. A decline in tidal volume, at onset of hyperoxia, was not a consistent finding in all individuals. PETCO2, end-tidal PCO2; Pmask, mask pressure; PETCO2, end-tidal PO2.](image-url)
Table 1. Results of grouped data for timing, ventilation, and resistance during room air control and sustained hyperoxia

<table>
<thead>
<tr>
<th>Variables</th>
<th>Control</th>
<th>Sustained Hyperoxia</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1, s</td>
<td>2.1 ± 0.1</td>
<td>2.1 ± 0.1</td>
</tr>
<tr>
<td>Tc, s</td>
<td>2.2 ± 0.1</td>
<td>2.0 ± 0.1</td>
</tr>
<tr>
<td>fck, breaths/min</td>
<td>14.6 ± 0.8</td>
<td>15.0 ± 0.8</td>
</tr>
<tr>
<td>PetCO₂, Torr</td>
<td>41.5 ± 0.8</td>
<td>39.1 ± 0.8†</td>
</tr>
<tr>
<td>Vt, liter</td>
<td>0.436 ± 0.03</td>
<td>0.507 ± 0.03*</td>
</tr>
<tr>
<td>Vl, l/min</td>
<td>6.2 ± 0.5</td>
<td>7.5 ± 0.6*</td>
</tr>
<tr>
<td>RUA, 1·s⁻¹·cmH₂O⁻¹</td>
<td>9.7 ± 1.1</td>
<td>7.1 ± 1.3</td>
</tr>
<tr>
<td>SaO₂, %</td>
<td>96.5 ± 1.1</td>
<td>98.8 ± 0.6†</td>
</tr>
<tr>
<td>Fck, %</td>
<td>20.1 ± 0.8</td>
<td>74.2 ± 9.7‡</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 10 subjects (see text for details). T1, inspiratory time; Tc, expiratory time; fck, frequency of breathing; PetCO₂, end-tidal PCO₂ level; Vt, tidal volume; Vl, minute ventilation; RUA, upper airway resistance; SaO₂, oxygen saturation; Fck, fraction of inspired O₂. *P < 0.05, †P < 0.01, ‡P < 0.001 vs. control.

Table 1 summarizes the results noted during control room air and sustained hyperoxia before onset of MV protocol. There was a significant increase in Vl, with a corresponding significant drop in PetCO₂ during exposure to sustained hyperoxia, before the onset of MV protocol. Thus the lower PetCO₂ observed during hyperoxia was likely a result of increased Vl upon exposure to sustained hyperoxia. A representative example of hyperventilation during sustained hyperoxia is shown in Fig. 1.

**MV Protocol**

In the nine participants who completed the MV protocol, the eupneic Vl during Hyp was significantly higher than Vl during sham exposure (7.2 ± 0.6 vs. 5.9 ± 0.9 l/min; P < 0.05), with a correspondingly lower eupneic PetCO₂ during Hyp than during sham exposure (37.6 ± 0.6 vs. 41.1 ± 0.6 Torr; P = 0.001). The CO₂ reserve was significantly larger during Hyp exposure relative to sham exposure (−3.8 ± 0.8 vs. −2.0 ± 0.3 Torr; P = 0.03) (Fig. 2A). Subsequently, the AT was significantly lower during Hyp relative to the sham study (33.3 ± 1.2 vs. 39.0 ± 0.7 Torr; P = 0.01) (Fig. 2A). This was associated with a significant decline in the hypocapnic ventilatory response under Hyp vs. sham conditions (2.5 ± 0.5 vs. 3.7 ± 0.5 l·min⁻¹·Torr⁻¹; P = 0.008, Fig. 2B).

**RESULTS**

Nine participants, (4 men and 5 women) completed the MV protocol of the study, age 23.6 ± 3.8 yr, body mass index 23.6 ± 3.0 kg/m², and neck circumference 34.2 ± 4.3 cm (means ± SD), while an additional participant completed only the baseline hyperoxia portion of the study, but was not able to maintain stable sleep during the MV protocol. Of the five women, four were studied in the follicular phase of their menstrual cycle, per reported date of menses; however, data on the fifth female participant was missing. The characteristics of the group of 10 was not different from the group that underwent MV protocol, five men and five women, age 23.4 ± 3.5 yr, body mass index 23.9 ± 3.0 kg/m², and neck circumference 34.4 ± 4.1 cm.

**Baseline Sustained Hyperoxia**

Sustained hyperoxia, before onset of MV protocol, was maintained for 21.9 ± 16.7 min (mean ± SD) in 10 participants. A representative example of hyperventilation during sustained hyperoxia is shown in Fig. 1.

**Statistical Analysis**

Results are presented as means ± SE, unless specified otherwise. A commercially available computer statistical package was used to analyze the data (Sigma Stat 3.11.0, SPSS). The level of statistical significance was set at P < 0.05. A sample size estimation showed that to obtain a 1-mmHg change in CO₂ reserve, with an estimated SD of 1 mmHg, an α-error set at 0.05 to obtain a statistical power of 80%, a sample size of 10 was required. Given that the SD obtained in our study was smaller, a sample size of nine participants who underwent MV protocol allowed adequate power.

During the baseline sustained hyperoxia period, comparisons between time points for control and hyperoxia periods were made for ventilation, timing, and RUA parameters, using paired t-test. When the normality test failed (Vt, Vl, and SaO₂), then Wilcoxon signed-rank test was used for comparison.

During MV protocol, paired t-tests were performed to compare eupneic PetCO₂, AT, and CO₂ reserve recorded during Hyp and sham exposures (normally distributed data). For nonparametric distributed data (hypocapnic ventilatory response), the Wilcoxon signed-rank test was used for comparison.

**Fig. 2.** A: comparisons of apneic threshold (AT) and CO₂ reserve under the two conditions, hyperoxia and room air. The major findings were that the AT was significantly lower and the CO₂ reserve was significantly higher during hyperoxia vs. sham room air exposure, *P < 0.05. B: group data for hypocapnic ventilatory response under the two conditions. There was a significant decline in the hypocapnic ventilatory response during hyperoxia vs. sham room air, *P = 0.008. Solid and shaded bars represent hyperoxia and sham room air trials, respectively.
DISCUSSION

Our study demonstrated several novel findings regarding the effect of hyperoxia on the control of breathing during NREM sleep. 1) Sustained hyperoxia resulted in hyperventilation manifesting by increased $V_t$ and a corresponding decrease in $P_{ETCO_2}$. 2) Sustained hyperoxia was associated with a decline in the hypocapnic ventilatory response, a widened CO$_2$ reserve, and reduced AT.

Hyperoxic Hyperventilation

We noted that sustained hyperoxia resulted in hyperventilation, manifesting as increased $V_t$ and reduced $P_{ETCO_2}$. Hyperoxia is defined as the level of PO$_2$ inspired that produces a neural tissue PO$_2$ greater than while breathing normobaric air (PO$_2$ > 160 Torr) (10, 27, 28). Multiple animal and human studies have shown hyperoxic hyperventilation, after an initial transient hypoventilation (3, 4, 5, 8, 17, 26, 42). The initial hyperventilation (15, 42), due to peripheral chemoreceptor inhibition, has not been demonstrated consistently (5, 15, 17, 20, 26, 42). Subsequent hyperventilation is likely of central origin (15, 20, 42) and manifests as increased $V_t$, commencing within 5 min of hyperoxia, and may be associated with an augmented hypercapnic response (20). Conversely, recent evidence in a canine model (36) showed that there is interdependence of peripheral and central chemoreceptors, and, in fact, the gain of the central chemoreceptors seems to be very dependent on the peripheral chemoreceptor activity (36). In our study, we observed an increase in $V_t$ after at least 10–15 min of hyperoxia, suggesting that the central chemoreceptors have been activated. Whether the peripheral chemoreceptor had an additive, hyperadditive, or hypoadditive effect (14) in our model cannot be determined from our protocol.

There are several potential mechanisms underlying hyperoxic hyperventilation. Hyperoxia may result in increased brain tissue PCO$_2$ via cerebral vasoconstriction (19) or the Haldane effect (22). Alternatively, hyperoxia may have a direct stimulatory effect on chemosensitive respiratory neurons (11, 27, 28, 29). For example, Mulkey et al. (28) demonstrated that hyperoxia was associated with increased production of reactive oxygen species and increased firing rate of central CO$_2$ chemoreceptors in the solitary complex neurons of the dorsocaudal medulla oblongata. Our findings are consistent with the aforementioned studies by demonstrating the presence of hyperoxic hyperventilation in sleeping humans. The potential mechanisms of hyperoxic hyperventilation in sleeping humans are not addressed by our study.

Hyperoxia and Susceptibility to Hypocapnic Central Apnea

We noted that hyperoxia mitigated the propensity to develop central apnea during sleep. Potential contributing factors include background increased ventilatory motor output, chemoreflex sensitivity, and sleep state stability. Our findings are consistent with previous studies demonstrating a salutary effect of increased ventilatory motor output on breathing stability, as evidenced by widened CO$_2$ reserve following central chemoreceptor stimulation with metabolic acidosis, or stimulation of the peripheral chemoreceptor with almitrine (30). Sustained hyperoxia may increase ventilatory motor output by cerebral vasoconstriction, either via direct effect of hyperoxia or a consequence of arterial hypocapnia. The net effect is reduced CO$_2$ washout, elevated brain tissue Pco$_2$, and increased H$^+$ in the medulla (14).

We observed that hypocapnic chemoreflex sensitivity declined during hyperoxia, as measured by the reduced ventilatory change for a given change in $P_{ETCO_2}$. Our findings with sustained hyperoxia are similar to previous studies demonstrating reduced CO$_2$ sensitivity following transient Hyp exposure (9, 46). Thus hyperoxia likely blunted the peripheral responsiveness to hypocapnia, resulting in lower hypocapnic ventilatory response.

Widening of the CO$_2$ reserve may be due to plant factors, which dampen the magnitude of hypocapnia for a given increase in ventilation. The development of hyperoxic hyperventilation and the concomitant decrease in eupneic $P_{ETCO_2}$ also suggest reduced “plant gain” (13), as a greater change in $V_t$ is required for a given decrease in eupneic $P_{ETCO_2}$ (Fig. 3, see legend).

Physiological Significance

Our findings provide a mechanistic explanation for the reported therapeutic effect of supplemental oxygen in patients with central sleep apnea, associated with high altitude (4), congestive heart failure, and idiopathic central apnea (16, 18, 33, 39). Potential mechanisms include decreased plant gain or reduced CO$_2$ chemoreflex sensitivity (17, 25, 46). Our findings are consistent with both mechanisms, as well as increased baseline ventilatory motor output, due to increased cerebral tissue PCO$_2$ or direct hyperoxic stimulation, producing a sustained increase in ventilation in our study. This widened the CO$_2$ reserve by lowering the eupneic CO$_2$, thus stabilizing respiratory control. Thus the aggregate effects of hyperoxia promoted breathing stability during NREM sleep. This may provide a therapeutic pathway for treating central sleep apnea.

![Fig. 3. Schematic representation of the relationship between minute ventilation ($V_t$) and $P_{ETCO_2}$ along the isometabolic curve. Note decreased eupneic $P_{ETCO_2}$ with hyperoxia (X), compared with sham exposure (Y), indicative of decreased plant gain. There is also a decrease in the slope of $V_t$/CO$_2$ with hyperoxia (solid line) compared with sham (dashed line), confirming a decline in the hypocapnic ventilatory responsiveness upon exposure to hyperoxia. The arrows indicate CO$_2$ reserve during the two exposure conditions: greater magnitude of CO$_2$ reserve with hyperoxia (solid arrow) compared with sham room air exposure (dashed arrow). Points A and B represent AT during hyperoxia and sham, respectively.](www.jap.org)
However, long-term safety and efficacy have not been established, given the potential for production of reactive oxygen species upon prolonged oxygen use in patients with central apnea and no evidence of hypoxemia.

Methodological Considerations

Sleep state instability may influence the AT and the hypocapnic ventilatory response; however, we analyzed trials with stable sleep state only. To achieve natural unaided sleep, we implemented moderate sleep curtailment on the night preceding the experimental protocol. Our own experience and published literature (37) demonstrate no adverse effect of moderate sleep curtailment in healthy humans on ventilatory control. In addition, study participants underwent similar sleep curtailment for both the hyperoxia and sham studies. Zolpidem was used to stabilize sleep in two individuals. It has no effect on ventilation or breathing stability and has been used by other investigators in similar studies (2, 46). Additionally, MV may induce neuromuscular inhibition if large VT (>200% of euapneic VT) were applied (21). Likewise, any volume effect on ventilation control would manifest under both hyperoxia and sham nights. It is also possible that a reduction in RDA may unload the upper airway and thereby increase airflow and Vt with reduced end-tidal CO2 levels (34) with hyperoxia; however, the effect of hyperoxia on RDA was not significant (Table 1), indicating that this was not a contributing factor to the observed findings. Additionally, Mahamed et al. (23) suggested that a decline in metabolism during sleep produces a decrease in plant gain and thereby a significant overnight reduction in chemoreflex thresholds and stable breathing in non-obstructive sleep apnea subjects. While this may have been a possibility in our study, the effect of reduced metabolism would have been a contributing factor during both hyperoxia and sham exposures and would not explain the overall decrease in plant gain noted during hyperoxia exposure alone, over and above the values noted during sham exposure. Finally, the study protocol involved delivery of a high FiO2 (PiO2 >250 Torr, FiO2 >50%) to ensure inhibition of the peripheral chemoreceptors. This level was higher than levels (1–5 l/min) used in clinical scenarios of heart failure with central chemoreceptors. This level was higher than levels (1–5 l/min) applied (21). Likewise, any volume effect on ventilation control would manifest under both hyperoxia and sham exposures and would not explain the overall decrease in plant gain and thereby a significant overnight reduction in chemoreflex thresholds.

In conclusion, hyperoxia stabilizes breathing in healthy individuals during NREM sleep by stimulating hyperventilation, consequently widening the CO2 reserve.

GRANTS

This work was supported by the Department of Veterans Affairs and the National Heart, Lung, and Blood Institute.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

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