Effects of nasal continuous positive airway pressure and oxygen supplementation on norepinephrine kinetics and cardiovascular responses in obstructive sleep apnea

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NORADRENERGIC ACTIVATION, as indicated by augmented sympathetic neural activity, elevated circulating norepinephrine (NE) levels, and elevated urinary NE excretion, is a hallmark of obstructive sleep apnea (OSA) (3, 4, 8). Cardiovascular consequences of this activation include high blood pressure and enhanced cardiac contractility, as well as adrenergic receptor desensitization (8, 10, 16–18). The elevated NE levels in OSA could be the result of an enhanced NE release rate and/or decreased NE clearance rate. We previously reported that OSA patients have an enhanced NE release rate under hypoxic conditions and a tendency toward decreased NE clearance (27).

Treatment of OSA with nasal continuous positive airway pressure (CPAP) reduces circulating levels of norepinephrine, as well as NE excretion (2, 8, 9, 11). The CPAP-induced reduction in NE is associated with a reduction in blood pressure, cardiac contractility, and restoration of desensitized β-adrenergic receptors (18, 19, 25).

The purpose of this study was to determine whether CPAP reduces NE levels by altering daytime release and/or clearance rate and whether such effects would be related to reductions in blood pressure. Considering prior observations that patients with OSA have a tendency toward diminished NE clearance and increased NE levels and that CPAP reduces NE levels, we hypothesized that CPAP treatment would lead to an increase in NE clearance and/or a decrease in NE release rate.

We compared CPAP to a placebo CPAP treatment and to an oxygen supplementation treatment. Nocturnal supplemental oxygen has been suggested by some as an alternative therapy in the noncompliant OSA patient (14, 21). In some OSA patients who cannot tolerate CPAP and are not candidates for a surgical procedure, supplemental oxygen therapy is associated with a reversal of OSA-related nocturnal hypoxemia but does not affect respiratory disturbance index (RDI) (14). The effect of supplemental oxygen on sympathetic activation in OSA has not been rigorously studied.

METHODS

Patients and screening. Patients were recruited from the community through advertisement and referral from sleep-disorder clinics. Screening criteria included clinical suspicion of OSA as per loud snoring with or without excessive daytime sleepiness. Because apneic patients frequently have hypertension (6), and because antihypertensive treatments have noticeable effects on the sympathetic nervous system (24), all hypertensive patients receiving such treatment were tapered off medication for at least 2 wk before participation in the study. Other inclusion criteria included weight being between 1.0 and 2.0 times the ideal body weight (15) and age between 30 and 65 yr. Patients were excluded if they were receiving medications known to affect sleep. Patients with other major medical disorders, including congestive heart failure, symptomatic obstructive pulmonary disease, history of narcolepsy, prior surgery for treatment of OSA, current alcohol or drug abuse, or psychosis were excluded.

Screening included a history and physical examination and complete blood count, chemistry panel, and electrocardiogram. Potentially eligible candidates underwent an unattended overnight home screening sleep study using the Stardust (Respironics, Marietta, GA) home sleep recording system. Subjects with an apnea-hypopnea index (AHI) >15 were then admitted for 3 nights to the University of California, San Diego (UCSD) General Clinical Research Center (GCRC) Gillin...
Laboratory of Sleep and Chronobiology, where full polysomnography confirmed the diagnosis of OSA (2, 11). Subjects with periodic limb movement >15 on baseline polysomnography were excluded from further participation. The same team of nighttime technicians and daytime technicians performed and scored the polysomnograms.

Sleep was recorded using the Grass Heritage (model PSG36-2, West Warwick, RI) sleep recording system using a standard montage. All records were scored according to Rechtshaffen and Kales criteria (22). Percent time less than 90% arterial oxygen saturation (Sao2 <90%) was determined and averaged over the nights. Apneas were defined as a decrement in airflow >90% from baseline for a period ≥10 s. Hypopneas were defined as a decrement in airflow ≥50% but <90% from baseline for a period ≥10 s. The number of apneas and hypopneas per hour of sleep were determined to obtain the AHI.

Fifty men and women completed screening and were admitted to the study. All patients gave signed consent to the protocol, which was approved by the UCSD Human Subjects Institutional Review Board.

Treatment design and randomization. Randomization took place on the second night of admission. Patients were randomized to a 2-wk therapeutic trial of nasal CPAP (n = 17), placebo CPAP (n = 17), placebo CPAP or nocturnal oxygen (n = 17). In the therapeutic CPAP group, conventional manual overnight CPAP titration was performed in increasing steps of 1–2 cmH2O until unequivocal obstructive apneas or hypopneas were controlled in the second or third rapid eye movement sleep period. All patients randomized to CPAP had an effective titration as defined by an AHI <10. Patients randomized to placebo CPAP or supplemental oxygen underwent a mock titration. On the third night of admission, patients slept with their assigned treatment.

Equipment for the three treatment arms was similar and consisted of a CPAP generator (Aria LX CPAP System, Respironics, Murrysville, PA), CPAP mask (Profile Light, Respironics), tubing, heated humidifier (Fisher and Pykel HC199, Auckland, New Zealand), and oxygen concentrator (Alliance, Healthdyne Technologies model 505, Marietta, GA). The concentrator could be switched to produce room air. The supplemental gas (room air or oxygen) was introduced into the CPAP system at the level of the humidifier. To maintain the blind of a CPAP generator (Aria LX CPAP System, Respironics, Murrysville, PA), patients slept with their assigned treatment.

Randomization took place on admission, patients slept with their assigned treatment.

When at the GCRC, patients had urine collected from 1700 to 2200, 2200 to 0600, and 0600 to 1700. We evaluated the adequacy of urine collection by measures of volume and creatinine excretion. Urine NE was measured by a catechol-O-methyltransferase-based radioenzymatic procedure with a purification step before assay (13). Urinary NE excretion is expressed in micrograms excreted per hour during wake (16 h, 0600–2200) and sleep (8 h, 2200–0600).

Blood pressure, heart rate, and plasma NE. Blood pressure and heart rate were assessed at a different time by using an automated monitor while the subject was supine. The means of three consecutive measurements were taken as the blood pressure and heart rate values. Under these supine conditions, blood was drawn for plasma NE levels and assayed as previously described (13).

Data analysis. Data were analyzed by two-way (group × time) ANOVA and hierarchical multivariable regression. Separate ANOVAs were run to test whether treatment led to a change in NE clearance and to test whether treatment led to a change in NE release rate. Distribution of all variables was evaluated by Levene’s test of equality of variances; parametric tests were used only in case of normal distribution. Initial relationships among variables were explored by Pearson correlations. Significance level was set at P < 0.05 for two-sided tests.

<table>
<thead>
<tr>
<th>Table 1.</th>
<th>Subject characteristics and treatment compliance data</th>
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<tbody>
<tr>
<td></td>
<td>CPAP</td>
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<tr>
<td>N</td>
<td>17</td>
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<tr>
<td>Men/women</td>
<td>15/2</td>
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<tr>
<td>Normotensive/hypertensive</td>
<td>9/8</td>
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<td>Age, yr</td>
<td>47.6±2.58</td>
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<td>Body mass index</td>
<td>31.7±1.4</td>
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<tr>
<td>Compliance, h/night</td>
<td>6.78±0.381</td>
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Values are means ± SE. CPAP, continuous positive airway pressure. Nightly compliance was averaged over 2 wk; no significant differences among groups.
Table 2. Pretreatment correlation coefficients among all subjects

<table>
<thead>
<tr>
<th></th>
<th>NE Clearance</th>
<th>NE Release</th>
<th>Plasma NE</th>
<th>Supine Plasma NE</th>
<th>NE Excretion, Day</th>
<th>NE Excretion, Night</th>
<th>Systolic BP</th>
<th>Diastolic BP</th>
<th>Heart Rate</th>
<th>Apnea-Hypopnia Index</th>
<th>SdO2 &lt; 90%</th>
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<tbody>
<tr>
<td>NE clearance</td>
<td>0.565†</td>
<td>0.616‡</td>
<td>0.480†</td>
<td>0.438‡</td>
<td>0.334†</td>
<td>0.338†</td>
<td>0.344†</td>
<td>0.330†</td>
<td>0.282†</td>
<td>0.263*</td>
<td>0.293†</td>
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<td>NE excretion, day</td>
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<td>NE excretion, night</td>
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<td>Systolic BP</td>
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<td>Diastolic BP</td>
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<td>Heart rate</td>
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<td>Apnea-hypopnia index</td>
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NE, norepinephrine; BP, blood pressure; SdO2, arterial O2 saturation from pulse oximetry. *P < 0.10; †P < 0.05; ‡P < 0.01.

Because NE clearance and release rate are not independent variables, these ANOVA tests were alpha adjusted. Data analyses were performed using the SPSS 12.0 programming package (Chicago, IL). All variables are presented as means ± SE.

RESULTS

Pretreatment. Table 1 presents subject characteristics and treatment compliance data. Body mass index (BMI) was computed as the ratio of body weight in kilograms divided by the square of height in meters (kg/m²). Before treatment, subjects randomized to the three treatment groups were similar in age, BMI, gender distribution, and hypertension distribution. Compliance with treatment was based on the average number of hours of use per night during the 2-wk treatment period. There was no significant difference among the three groups in treatment compliance (F = 1.693, P = 0.195).

Before treatment, among all patients, blood pressure was related to both day and night NE excretion rates (P < 0.05) (Table 2). AHI was related to NE release rate (P < 0.01) and day and night NE excretion rates (P < 0.05). SdO2 < 90% correlated with NE release rate (P < 0.01), supine plasma NE levels (P < 0.01), and day and night NE excretion rates (P < 0.01).

Posttreatment. Table 3 presents the effects of treatment on AHI, SdO2 < 90%, blood pressure, and heart rate. There were no significant pretreatment differences among the groups for any of these variables. AHI was significantly reduced in the CPAP condition (F = 28.9, P < 0.001) but not in the oxygen or placebo CPAP conditions. SdO2 < 90% was significantly reduced in the CPAP and the oxygen conditions (F values >6.3, P < 0.05) but not in the placebo CPAP condition. Systolic (F = 7.8, P = 0.013) and diastolic (F = 6.1, P = 0.026) blood pressure and heart rate (F = 7.7, P = 0.014) were decreased in response to CPAP but not the oxygen or placebo CPAP.

Two weeks of CPAP led to a significant increase in NE clearance (F = 9.53, P = 0.01) (Table 4 and Fig. 1). The enhanced clearance of NE was due to an expanded volume of distribution (F = 7.7, P = 0.017), not to a shortened half-life (P = 0.06) (Table 4). NE clearance, volume of distribution, and half-life were unchanged after either oxygen or placebo CPAP. Supine plasma NE levels were reduced after CPAP (F = 7.9, P = 0.018) but unchanged after either oxygen or placebo CPAP. Daytime NE excretion was reduced after 2 wk of CPAP treatment (F = 20.8, P < 0.001) and oxygen treatment (F = 9.9, P < 0.01) but unchanged after placebo CPAP. Nighttime NE excretion was reduced after CPAP treatment only (F = 5.6, P < 0.05). NE release rate was unchanged with any treatment (Fig. 1).

In an effort to better understand the role of NE in blood pressure and heart rate responses to treatment, we conducted a series of multiple regression analyses examining possible predictors of posttreatment levels of systolic and diastolic blood pressure and heart rate. Dependent variables were entered into the regression in blocks as follows: block 1: age, BMI, gender, and diagnosis of hypertension; block 2: pretreatment AHI, SdO2 < 90%, and the respective pretreatment blood pressure or heart rate; block 3: pretreatment NE clearance, NE release rate, supine plasma NE, and daytime and nighttime NE excretion; block 4: posttreatment AHI, SdO2 < 90%, and the respective posttreatment blood pressure or heart rate; block 5: posttreatment NE clearance, NE release rate, supine plasma NE, and daytime and nighttime NE excretion.

Posttreatment systolic blood pressure was predicted by pretreatment systolic blood pressure (β = 0.450, P = 0.005), posttreatment NE clearance (β = −0.836, P = 0.001), and posttreatment NE release rate (β =

Table 3. Treatment effects on apnea-hypopnia index, SdO2 < 90%, and blood pressure and heart rate

<table>
<thead>
<tr>
<th></th>
<th>CPAP</th>
<th>Oxygen</th>
<th>Placebo CPAP</th>
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<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>Apnea hypopnia index*</td>
<td>65.0±8.3</td>
<td>2.56±0.57</td>
<td>61.8±9.4</td>
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<tr>
<td>SdO2 &lt; 90%‡</td>
<td>8.9±3.9</td>
<td>0.07±0.08</td>
<td>5.0±2.4</td>
</tr>
<tr>
<td>Systolic BP, mmHg‡</td>
<td>155.2±4.5</td>
<td>145.1±5.1</td>
<td>149.5±3.4</td>
</tr>
<tr>
<td>Diastolic BP, mmHg§</td>
<td>84.2±2.6</td>
<td>79.5±3.2</td>
<td>81.3±1.8</td>
</tr>
<tr>
<td>Heart rate, beats/min</td>
<td>68.0±1.8</td>
<td>62.5±1.9</td>
<td>71.9±2.8</td>
</tr>
</tbody>
</table>

Values are means ± SE. Pre, before treatment; Post, after treatment. *Reduction with CPAP, P = 0.000; †reduction with CPAP (P = 0.023) and O2 (P = 0.036); ‡reduction with CPAP; SBP, P = 0.013; HR, P = 0.014; §reduction with CPAP, P = 0.026.

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Posttreatment heart rate was predicted by pretreatment heart rate and AHI. Only CPAP significantly lowered daytime blood pressure, whereas neither oxygen nor placebo reduced daytime blood pressure. These results are consistent with our previous finding that AHI is an important predictor of daytime blood pressure in OSA patients (25). The reduction in daytime blood pressure is likely to be due to a reduction in sympathetic nerve activity by CPAP (26). This is consistent with our previous finding of a significant decrease in day-time sympathetic nerve activity by CPAP (21), but we have previously found a suggestion of a decrease in renin activity (27). Our finding is also consistent with our previous finding of a significant decrease in daytime sympathetic nerve activity by CPAP (21), but we have previously found a suggestion of a decrease in renin activity (27).

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sure; its effect was about twice as large as the nonsignificant decrease seen with oxygen. Both CPAP and oxygen lowered daytime urine NE; the effect of CPAP was about twice as large as oxygen. CPAP also lowered nighttime urine NE, but oxygen failed to do so. This is not surprising, because oxygen failed to alter the number of nighttime apneas, and sympathetic nerve activity increases markedly after apneic episodes (25).

We previously reported that CPAP reduces daytime ambulatory mean arterial blood pressure to the same extent as placebo CPAP but that CPAP leads to a much greater decrease in nighttime ambulatory mean arterial blood pressure compared with placebo CPAP (5). This previous study was of 1-wk duration as opposed to 2-wk duration herein. Studies by Becker et al. (1) and Pepperell et al. (20) were of longer duration and found blood pressure to decrease with CPAP. It is likely that the beneficial effects of CPAP on blood pressure are more evident with longer treatment.

OSA is associated with hypertension. The proposed mechanism for the association is sympathetic activation (3, 4, 8). Intermittent hypoxia causes hypertension in rats, but chronic hypoxia does not usually cause hypertension in humans (7). On the other hand, recovery from individual episodes of apnea increases sympathetic nerve activity and blood pressure. Our study suggests that apneic episodes are more important than hypoxia in increasing plasma and urine NE and blood pressure. We also examined possible predictors of posttreatment blood pressure and heart rate. We found that posttreatment systolic blood pressure was best predicted by a combination of pretreatment systolic blood pressure and posttreatment NE clearance and release rates (e.g., a lower posttreatment blood pressure was associated with a lower pretreatment blood pressure, a higher posttreatment NE clearance, and a lower posttreatment NE release rate). We are not aware of evidence for a direct link between a change in NE clearance and cardiovascular consequences. Although increased clearance decreases plasma NE levels, the decrease is too small to have direct measurable consequences. An indirect link between NE clearance and cardiovascular consequences is that NE clearance is useful in calculating NE release rate. NE release rate did not change with CPAP therapy despite the decrease in plasma NE levels. In contrast, urine NE levels did decrease with CPAP. An unchanged NE release rate and a diminished urine NE level after CPAP imply that CPAP decreases renal sympathetic nerve activity. Decreased renal sympathetic nerve activity might decrease sodium retention and renin, with lower blood pressure as a consequence. We did find lower blood pressure after CPAP.

As described in METHODS, we took the opportunity to assess plasma NE at two different time points in the study. The general magnitude and direction of change of the two plasma NE levels in Table 4 were very consistent, although only the supine plasma NE level taken with the blood pressure and heart rate assessment was significantly lower at posttreatment in the CPAP group.

Our randomization of apneic patients to treatment was successful in that there were no significant pretreatment differences among the three groups in terms of apnea severity, age, weight, or blood pressure. Before treatment, among all patients, apnea severity, as indicated by AHI and $S_aO_2<90\%$, was related to higher plasma NE levels and higher NE excretion, confirming prior observations of increasing noradrenergic activation with increasing apnea severity (3, 4, 8).

In summary, 2 wk of CPAP treatment for OSA resulted in increased NE clearance rate. Posttreatment systolic blood pressure was related to pretreatment systolic blood pressure and posttreatment NE clearance and NE release rate. CPAP lowered urinary NE and blood pressure more effectively than oxygen supplementation, suggesting that apneic episodes might be more important than hypoxia in determining sympathetic activity and blood pressure.

GRANTS

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REFERENCES


