Neuromechanical control of upper airway patency during sleep

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OBSTRUCTIVE SLEEP APNEA is a prevalent disorder characterized by repetitive upper airway obstruction that results in recurrent hypoxemia and arousal from sleep (32, 48). Although it is well known that pharyngeal occlusion is the primary cause of sleep apnea, the precise mechanisms leading to upper airway obstruction are incompletely understood. Moreover, the critical pressure of the upper airway (Pcrit), a measurement of upper airway mechanical loads and dynamic responses to airflow obstruction (active critical pressure). Compared with normal subjects, sleep apnea patients demonstrated elevated mechanical loads as demonstrated by higher passive mechanical properties (passive critical pressure) and active dynamic responses to upper airway obstruction (active critical pressure). Compared with normal subjects, sleep apnea patients demonstrated elevated mechanical loads as demonstrated by higher passive critical pressures \(-0.05 \text{ (SD 2.4)} \text{ vs. } -4.5 \text{ cmH}_2\text{O (SD 3.0)}, P = 0.0003\). Dynamic responses were depressed in sleep apnea patients, as suggested by failure to lower their active critical pressures \(-1.6 \text{ (SD 3.5)} \text{ vs. } -11.1 \text{ cmH}_2\text{O (SD 5.3)}, P < 0.0001\) in response to upper airway obstruction. Moreover, elevated mechanical loads placed some normal individuals at risk for sleep apnea. In this subset, dynamic responses to upper airway obstruction compensated for mechanical loads and maintained airway patency by lowering the active critical pressure. The present study suggests that increased mechanical loads and blunted neuromuscular responses are both required for the development of obstructive sleep apnea.

obstructive sleep apnea; critical pressure; mechanical properties; neuromuscular control

Dynamic neuromuscular control of the upper airway (17, 36, 37, 48, 68) differs between sleep apnea patients and normal subjects, particularly during wakefulness. Specifically, during the waking state, it has been proposed that patients with anatomically narrowed upper airways require increased genioglossal muscle activity to compensate for the narrowing of the upper airway. Dynamic responses to upper airway obstruction can compensate for pharyngeal mechanical loads and stabilize airway patency during both wake and sleep (35, 49, 58–60). Acute upper airway obstruction results in alterations in lung volume, intraluminal airway pressures, and gas exchange, which activate the upper airway musculature and lower pharyngeal collapsibility (30, 35, 49, 58–60). Several investigators have suggested that dynamic responses to upper airway obstruction require coordinated action among numerous rather than any single pharyngeal muscle (2, 9, 25, 26, 52). Despite the presence of extensive literature, the extent to which both mechanical loads and dynamic neuromuscular responses contribute to airflow obstruction has not been systematically evaluated during sleep.

The major goal of this study was to quantitate the effect of upper airway mechanical loads and dynamic responses on sleep apnea pathogenesis. We hypothesized that compared with normal subjects, sleep apnea patients would be characterized by elevations in mechanical loads and impaired dynamic responses to airflow obstruction. In contrast, normal individuals would maintain upper airway patency during sleep due to reduced mechanical loads and/or vigorous dynamic responses in the presence of elevated mechanical loads. We utilized established methods for characterizing upper airway mechanical properties and dynamic responses to airflow obstruction to test these predictions. Since obesity, age, and sex are known risk factors for sleep apnea, our study groups were carefully matched for these factors.

MATERIALS AND METHODS

Study Population

Patients from the Johns Hopkins Sleep Disorders Center with moderately severe obstructive sleep apnea [apnea-hypopnea index (AHI) > 20 events/h] and a matched normal group of healthy volunteers from the community (AHI < 5 events/h and flow-limited breathing for less than half the night) were recruited. The groups were matched for age, sex, and body mass index (BMI). The study was approved by the institutional review board on human research, and all subjects provided written informed consent.

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Assessment of Sleep

An overnight sleep study was performed in subjects to determine the presence or absence of obstructive sleep apnea using techniques previously described (46). Sleep staging and arousals were scored using standard criteria (47). Airflow was monitored using a differential pressure transducer (Validyne ±2 cmH_2O; Northridge, CA) connected to nasal cannula. Thoracoabdominal movements were monitored using piezoelectrode strain gauges (Sleepmate, Midlothian, VA), and oxyhemoglobin saturation was monitored continuously via pulse oximetry (Ohmeda, Louisville, CO). Signals were acquired digitally for obstructive apneas and hypopneas as previously described (46). Severity of obstructive sleep apnea was defined by the AHI as determined by the number of obstructive apneas and hypopneas per hour.

Experimental Set-Up for Pharyngeal Critical Pressure Measurements

Following the baseline sleep study, patients underwent polysomnography while wearing a tight-fitting nasal mask for an additional one to two nights. Signals were amplified (Grass 78D Polygraph, Grass Instruments, Quincy, MA) and acquired digitally (Windaq, Akro, OH). Nasal pressure (P_N) was measured continuously at the level of the mask, and airflow measurements were obtained using a pneumotachograph (Hans Rudolph, Kansas City, MO) attached to a differential pressure transducer placed between the nasal mask and a continuous positive airway pressure (CPAP) unit designed to apply pressures between −20 and + 20 cmH_2O. We attempted to minimize the undue influence of mask and mouth leaks on the bias flow in the breathing circuit with customized, well-fitted masks and by detecting mouth leak with an oral thermistor. Respiratory effort was monitored via a Hyatt-type esophageal balloon (Ackrad Laboratories, Cranford, NJ) placed perinasally for monitoring esophageal pressure (11 of 16 normal patients and 11 of 16 sleep apnea subjects) and/or a piezoelectrode abdominal strain gauge. Patients slept in the supine position with one pillow under the head during the measurement periods.

Partitioning the Pharyngeal Critical Pressure

After the baseline sleep study, pharyngeal critical pressure measurements were obtained during sleep and partitioned between its mechanical (3, 43, 54) and dynamic neuromuscular components (57, 63), as previously reported. During the passive state, the critical pressure (passive Pcrit) of the hypotonic upper airway reflects its mechanical properties (54). During sleep, reductions in P_N are associated with progressive increases in neuromuscular activity (34). Under these conditions, the critical pressure can be obtained and reflects the recruitment of dynamic responses to upper airway obstruction, which cannot prevent airflow occlusion (active Pcrit).

Assessment of Passive Critical Pressure

As previously demonstrated by other investigators (19, 54, 65), a hypotonic (passive) state was induced by raising P_N to a level sufficient to eliminate inspiratory flow limitation (holding pressure). When inspiratory flow limitation was abolished, reduced neuromuscular activity [based on genioglossal electromyogram (EMG_GG)] or alae nasi electromyogram (EMG_AN) activity] was observed. During stable, non-rapid eye movement (NREM) sleep, the passive Pcrit was determined by abruptly lowering the P_N for five breaths and returning to the holding pressure (6, 43). P_N was abruptly reduced to increasingly lower P_Ns after reestablishing at least 1 min of stable sleep at the holding pressure. A minimum of two series of stepwise reductions in P_N by 1–2 cmH_2O that eventually encompassed zero airflow (Pcrit) was collected (see Fig. 1, passive). If an arousal occurred, the protocol was resumed after subjects reinitiated stage 2 NREM sleep for at least 3 min. Breaths associated with microarousals from sleep were excluded from analyses.

Assessment of the Active Critical Pressure

A standardized protocol for assessing the active Pcrit was implemented as previously described (11, 12, 53, 55–57, 63). After at least 3 min of stable stage 2 sleep at holding pressure, the P_N was reduced in a step-wise fashion by 1–2 cmH_2O and sustained for at least 10 min of NREM sleep before the P_N was reduced again. As P_N was sequentially lowered, stable flow-limited breathing was first observed (see Fig. 1, active) followed by periods of recurrent hypopneas and apneas. The P_N was lowered until apneas developed or the individual developed prolonged awakenings. If a prolonged awakening occurred, the protocol was resumed after patients reinitiated 3 min of stable stage 2 NREM sleep or if there was a consistent, stable pattern of hypopneas or apneas during stage 1 sleep that prevented the establishment of deeper levels of NREM sleep.

EMG_GG Monitoring

To document the differences in neuromuscular activity between the passive and active state, EMG_GG was monitored in a subsample of apneic (n = 5) and normal (n = 5) subjects. Two fine wire-hook needles were placed perorally, as previously described (36). The raw EMG_GG signal was amplified and band-pass filtered between 30 and 3,000 Hz (Grass 78D Polygraph, Grass Instruments, Quincy, MA) (36). The signal was rectified and integrated (time constant 100 ms) to generate a moving time-average signal (Windaq Advanced CODAS; DATAQ Instruments; Akron, OH). The EMG_GG signal was quantified as a percentage of maximal awake maneuver (tongue thrust or maximal tongue protrusion against the maxillary ridge) (36). At least three of each maneuver were obtained until a consistent maximal response was achieved.

Data Analysis

Passive and active pressure-flow analyses. The passive Pcrit of the upper airway was determined by plotting the maximal inspiratory airflow (VImax) from breaths 2–5 against P_N under the hypotonic conditions during stable non-REM sleep (3, 43). Each of these breaths was assessed for the presence or absence of inspiratory airflow limitation. To determine VImax, we determined the level of bias flow in the breathing circuit at each P_N level. Our measurement assumed that inspiratory and expiratory tidal volumes are equal over breaths 2–5. Under these circumstances, the mean airflow level will equal the bias flow rate through the breathing circuit. The mean flow rate was then used to establish a baseline zero flow level for measurements of maximal inspiratory airflow. When esophageal pressure measurements were present for a subject, inspiratory flow limitation was defined as the presence of a plateau in inspiratory airflow in association with a continued fall in esophageal pressure by at least 1 cmH_2O beyond the onset of the plateau. Flow limitation in the absence of esophageal pressure was determined using established criteria (18, 33). Flow limitation was considered to be present when a flattened flow vs. time contour was visualized. Breaths associated with arousal were excluded from analyses. The flow-limited segment of the VImax vs. P_N relationship was identified using a median segmented regression approach as previously described (43). The regression equation was solved for Pcrit (P_N at which zero airflow is present; Fig. 2). The resistance upstream to the site of obstruction (passive Rus) was calculated as the inverse of the regression slope (63).

Determination of the active Pcrit was calculated in a similar fashion. When stable flow limitation was present, P_N and VImax were obtained from nine breaths at the end of a 10-min period of stable NREM sleep. At P_Ns where the predominant pattern of breathing was periodic, the last three breaths of the final three hypopneas or apneas at each P_N level were sampled. Median segmented regression of VImax vs. P_N identified the flow-limited segment of the pressure-flow relationship and provided the active Pcrit and the active Rus (Fig. 2).
The difference between the active and passive Pcrit (ΔPcritA−P; Fig. 2) was considered as a measure of the strength of dynamic neuromuscular responses to upper airway obstruction. We recognized that lowering the PN would eventually result in periodic obstructive hypopneas and obstructive apneas and arousals from sleep (24). Under such circumstances, sleep and breathing instabilities may confound our assessment of the dynamic responses to upper airway obstruction and the active Pcrit. To address this issue, we identified a PN transition threshold between periods of stable and unstable sleep and breathing in the active condition. This threshold was defined by the level of PN and corresponding VImax at which instability was observed (Fig. 2, point A). The PN range above the transition threshold was used to define the steady-state portion of the active pressure-flow relationship.

To determine dynamic responses to sustained periods of upper airway obstruction during periods of stable stage 2 sleep and breathing, two parameters were derived. First, the PN at the transition threshold during the active condition was compared with the PN of the passive pressure-flow relationship at the same level of VImax (see Fig. 2, point B; ΔPcritA−P). ΔPcritA−P represented the subject’s ability to preserve upper airway patency during steady-state sleep and maintain stable breathing patterns by recruiting dynamic neuromuscular responses (analogous to ΔPcritA−P). Second, we examined the level of airflow obstruction required to induce periodic breathing in normal and sleep apnea subjects. The subject’s susceptibility to periodic breathing was defined as the level of VImax at the transition threshold at which periodicity breathing began along the active pressure-flow relationship (transition threshold; see Fig. 2, point A).

In one normal subject, measurements of passive and active pressure-flow relationships were obtained during stage 3 sleep due to insufficient data collected during stage 2 sleep. Sensitivity analyses including and excluding the data collected in this subject demonstrated no significant differences in the results. The data for the subject were therefore included for all analyses. In three normal females (see Table 2), the active Pcrit was indeterminate due to awakenings from sleep at negative PN levels. Nevertheless, before the awakenings, subjects 5, 9, and 16 demonstrated partial upper airway obstruction (i.e., inspiratory flow-limitation) at a PN of -7.2, -8.4, and -13.7 cmH2O, respectively. In these three subjects, the active Pcrit was assumed to be equal to the lowest PN associated with flow-limited breathing before arousal. Imputing the active Pcrit with a value that was equal to the lowest PN obtained would increase the average active Pcrit and decrease the PcritA−P in the normal group and thus bias against our primary hypothesis. Sensitivity analyses of the active Pcrit and compensatory neuromuscular responses (ΔPcritA−P) excluding these three subjects did not change our findings. Therefore, we present the active Pcrit and ΔPcritA−P data in RESULTS excluding these three subjects. In contrast, ΔPcritA−P and the VImax at the transition threshold

![Fig. 1. Polysomnographic recording in a normal subject at a nasal pressure (PN) of -2.5 cmH2O during stable stage 2, non-rapid eye movement (NREM) sleep.](image-url)
were obtained in the three normal female subjects, whose data were therefore included for analyses.

**EMGG analyses.** Tonic and peak phasic EMGG values were determined for breaths at a P\(_T\) level equivalent to the passive Perit during the passive and active conditions (see Fig. 1). Tonic activity was defined as the lowest activity present during expiration. Peak phasic activity was defined as the maximal activity during inspiration.

The difference between tonic EMGG activity during the passive condition (Fig. 1, bracket B) and holding pressure (Fig. 1, bracket A) was calculated. Similarly, the difference between tonic EMGG activity during the active condition (Fig. 1, active) and holding pressure (Fig. 1, bracket A) was determined. The difference represents the relative activation of upper airway tonic EMGG during passive or active conditions compared with the holding pressure level. Corresponding calculations were performed to determine the relative activation of peak phasic EMGG activity during passive or active conditions compared with the holding pressure level. The change in tonic and peak phasic EMGG activity from the passive to the active conditions compared with the holding pressure level. The change in tonic and peak phasic EMGG activity from the passive to the active conditions compared with the holding pressure level.

**Statistical analysis.** All statistical analyses were performed using STATA 8 (Stata, College Station, TX). The primary outcomes in the study were the differences between the active and passive Perit (\(\Delta\text{Perit}_{A-P}\)), the difference in pressures between the active and passive conditions at the \(V_{\text{max}}\) transition threshold (\(\Delta P_{A-P}\)), the passive Perit, and the active Perit between apneic and normal subjects. Secondary outcomes included differences in \(\Delta\text{EMGG}_{A-P}\) and \(\Delta\text{EMGG}_{A-P}\) at which periodic breathing began in the active condition, and tonic and peak phasic EMGG between the two groups. Correlations between tonic or peak phasic \(\Delta\text{EMGG}_{A-P}\) and \(\Delta\text{EMGG}_{A-P}\) were examined using Pearson product-moment correlation. In addition, a composite passive and active pressure-flow relationship for normal subjects and sleep apnea patients was created by determining the median slope and intercept for each condition and disease state. Variables were not normally distributed; therefore the Wilcoxon rank-sum test was used for nonpaired comparisons, and the sign-rank test was used for paired comparisons. Chi-square analysis was used to test proportions. Statistical significance was assumed for \(P < 0.05\). Results are presented as means (SD) unless otherwise noted.

**RESULTS**

**Subject Characteristics**

Sixteen subjects with obstructive sleep apnea and sixteen normal subjects were recruited for the study. There were no significant differences between the two groups with respect to demographic characteristics (see Table 1) as planned by study design. Table 1 also demonstrates the sleep study characteristics of the two groups. Sleep apnea patients demonstrated increased stage 1 sleep, decreased stage 2 sleep, an elevated AHI in NREM and REM sleep, and a lower average nadir oxyhemoglobin value in both NREM and REM sleep compared with normal subjects; otherwise the two groups exhibited similar polysomnographic characteristics. In Table 2, subject characteristics and upper airway measurements are presented.

**Passive Properties**

The results for passive Perit are shown for each group in Fig. 3A. The mean (SD) holding pressure was 9.0 (SD 2.3) and 5.7 cmH\(_2\)O (SD 1.9) \((P = 0.0007)\) for obstructive sleep apnea patients and normal subjects, respectively. The mean passive Perit was elevated in patients with obstructive sleep apnea compared with normal subjects \([-0.05 \text{ (SD 2.4) and } -4.5 \text{ cmH}_2\text{O (SD 3.0), respectively; } P = 0.0003\), suggesting increased airway collapsibility under conditions of reduced neuromuscular activity. However, there was no significant difference in the passive Perit between obstructive sleep apnea

| Table 1. Summary of demographic and polysomnography data for normal subjects and OSA patients |
|---------------------------------|-----------------|-----------------|
| Variable                        | Normal Subjects | OSA Subjects |
| Age, yr                         | 38.1 (11.9)     | 40.1 (10.6)    |
| Body mass index, kg/m\(^2\)     | 29.4 (5.1)      | 29.8 (5.0)     |
| Sex, M/F                        | 9/7             | 11/5           |
| Total sleep time, min           | 376.9 (52.0)    | 408.1 (83.9)   |
| Sleep efficiency, %             | 89.8 (6.7)      | 89.5 (7.1)     |
| Wakefulness after sleep onset, min | 37.4 (27.3)   | 40.5 (31.0)    |
| Sleep stage, % of total sleep time | 11.7 (6.1)    | 25.6 (16.8)    |
| Stage 1*                        | 68.7 (8.7)      | 55.0 (14.8)    |
| Stage 2*                        | 4.4 (7.1)       | 1.7 (3.0)      |
| Stages 3 and 4                  | 15.2 (7.6)      | 17.8 (4.5)     |
| Rapid eye movement              | 54.7 (17.7)     | 52.4 (34.5)    |
| Breathing events, events/h      | 2.1 (1.6)       | 6.7 (6.3)      |
| NREM AHI                        | 25.4 (7.2)      | 26.0 (5.6)     |
| REM AHI                         | 24.5 (12.9)     | 32.4 (11.2)    |
| Average length of events, s     | 97.5 (1.4)      | 96.0 (2.9)     |
| NREM                            | 97.2 (1.7)      | 95.4 (3.8)     |
| REM                             | 94.1 (2.7)      | 90.4 (4.5)     |
| Arterial oxyhemoglobin saturation, % | 78.7 (6.6)   | 87.8 (7.6)     |

Values are means (SD). M, male; F, female OSA, obstructive sleep apnea; REM, rapid eye movement; NREM, non-rapid eye movement; AHI, apnea-hypopnea index. *P < 0.05, OSA vs. normal subjects.
patients and normal subjects [18.6 (SD 6.5) and 24.0 cmH₂O·l⁻¹·s⁻¹ (SD 15.0), respectively; \( P = 0.27 \)].

**Active Properties**

The mean active \( P_{crit} \) (see Fig. 3A) was also significantly elevated in obstructive sleep apnea patients compared with normal subjects [−1.6 (SD 3.5) and −11.1 cmH₂O (SD 5.3), respectively; \( P < 0.0001 \), suggesting increased upper airway collapsibility during conditions of intact neuromuscular activity. There was no significant difference in the active \( R_u \) between obstructive sleep apnea patients and normal subjects [22.5 (SD 10.3) and 31.5 cmH₂O·l⁻¹·s⁻¹ (SD 18.3), respectively; \( P = 0.17 \)].

**Dynamic Responses to Upper Airway Obstruction**

Dynamic responses to upper airway obstruction were greater in normal subjects than sleep apnea patients, as reflected by the \( \Delta P_{crit,A-P} \) [−6.9 (SD 5.7) vs. −1.6 cmH₂O (SD 2.4), respectively; \( P = 0.0004 \)] and the \( \Delta P_{A-P} \) [−6.1 (SD 5.4) vs. −0.8 cmH₂O (SD 2.2), respectively; \( P = 0.0006 \)]. The mean passive and active pressure-flow relationships are shown for normal subjects and obstructive sleep apnea patients in Fig. 4.

To determine whether normal subjects and sleep apnea patients differed in their tendency to develop periodic breathing, we compared \( V_{max} \) at the transition threshold between the two groups (Figs. 2 and 4). \( V_{max} \) at the transition threshold was similar in both groups [263 (SD 62) and 217 ml/s (SD 82) in normal and sleep apnea subjects, respectively; \( P = 0.08 \)], indicating that both groups developed periodic breathing at comparable levels of airflow obstruction.

Differences in dynamic responses to upper airway obstruction in normal compared with and apneic subjects could be related to differences in upper airway mechanical loads (i.e., passive \( P_{crit} \)) between the two groups. To address this concern, we compared the dynamic responses to upper airway obstruction in a subgroup of normal subjects \( [n = 7 \text{ (6 male, 1 female)}] \); age 41.4 yr (SD 10.2), BMI 29.0 kg/m² (SD 5.1)] and sleep apnea patients \( [n = 6 \text{ (4 male, 2 female)}] \); age 35.3 yr (SD 10.7), BMI 29.8 kg/m² (SD 5.5); \( P > 0.2 \) for all characteristics] with comparable passive \( P_{crit} \) [−2.0 (SD 2.3) vs. −2.4

### Table 2. Individual demographic and upper airway characteristics of participants

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**Normal subjects**

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Individual data for normal subjects and OSA patients. BMI, body mass index; \( P_{crit} \), critical pressure; \( R_u \), upstream resistance; \( \Delta P_{crit,A-P} \) = active \( P_{crit} \)−passive \( P_{crit} \); \( \Delta P_{A-P} \) = difference in active and passive nasal pressure at transition threshold (see Fig. 2).
cmH₂O (SD 1.4), respectively]. Despite comparable mechanical loads (Fig. 3B), the normal subjects had greater dynamic responses to upper airway obstruction than sleep apnea patients as demonstrated by ΔPcritA−p [−8.0 (SD 7.4) vs. 2.2 cmH₂O (SD 2.2), respectively; P = 0.03] and ΔPcritA−p [−6.0 (SD 3.7) vs. −2.2 cmH₂O (SD 2.5), respectively, P = 0.03].

**EMG_{GG} Responses**

Tonic and peak phasic EMG_{GG} activity were studied in a subsample of obstructive sleep apnea subjects [n = 5 (4 males, 1 female) age 40.2 yr (SD 11.3), BMI 31.4 kg/m² (SD 6.7)] and normal subjects [n = 5 (4 males, 1 female), age 42.2 yr (SD 13.6), BMI 28.2 kg/m² (SD 5.9); P > 0.5 for all characteristics]. The change in tonic EMG_{GG} activity between the passive and holding pressure states compared with the change in tonic EMG_{GG} activity between the active and holding pressure states demonstrated significant differences in normal subjects [4.7% (SD 4.2) vs. 14.1% (SD 13.9), P = 0.03] and apneic subjects [2.4% (SD 2.1) vs. 12.7% (SD 9.7), P = 0.03]. Similarly, the change in peak phasic EMG_{GG} activity between passive and

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**Fig. 3.** Passive and active upper airway critical pressure (P_{crit}) measurements in patients with obstructive sleep apnea (OSA) and age-, sex-, and body mass index-matched normal subjects. A: data for all subjects. Differences in passive P_{crit} and active P_{crit} between normal subjects and sleep apnea patients demonstrated statistical significance (P < 0.001). Furthermore, the difference in critical pressure between the passive and active states was greater in normal subjects compared with OSA patients (P < 0.001). B: data for subjects matched on the level of passive P_{crit}. Despite comparable passive P_{crit} (mechanical loads), normal subjects significantly lowered the active P_{crit} further than sleep apnea subjects [ΔP_{crit,A−p} 8.0 (SD 7.4) vs. 2.2 cmH₂O (SD 2.2), respectively, P < 0.05].

**Fig. 4.** Composite passive and active pressure-flow relationships in the normal group and obstructive sleep apnea group. There is a significant left shift in the active pressure-flow relationship seen in the normal group compared with the sleep apnea group, resulting in a lower active critical pressure (active P_{crit}) and a less collapsible upper airway. Variability in passive and active P_{crit} is represented by SD bars. In addition, the variability in P_{N} and V_{max} at the transition threshold (threshold at which periodic breathing begins) as represented by SD bars is displayed.
holding pressure states compared with the change in peak phasic EMG activity between active and holding pressure states demonstrated significant differences in normal subjects [9.7% (SD 4.1) vs. 22.6% (SD 10.8), P = 0.03] and apneic subjects [6.1% (SD 9.1) vs. 31.2% (SD 18.5), P = 0.03]. However, no significant difference in the tonic EMG activity or peak phasic EMG activity was found between normal subjects and obstructive sleep apnea patients during either the holding pressure, passive, or active conditions. Furthermore, no significant relationship between any measure of EMG activity and ∆PcritA–P or ∆PA–P was found.

DISCUSSION

We demonstrated that patients with obstructive sleep apnea were characterized by defects in upper airway mechanical properties and dynamic responses to upper airway obstruction compared with matched normal controls, as evidenced by elevations of upper airway critical pressures under passive and active conditions. In sleep apnea patients, the passive Pcrit was uniformly elevated to levels known to produce severe airflow obstruction during sleep, suggesting that mechanical loads play a key role in the pathogenesis of obstructive sleep apnea. The passive Pcrit was also elevated to a similar degree in a subgroup of our normal subjects, suggesting that some normal individuals have mechanical defects which place them at risk for the disorder. Despite the presence of elevated mechanical loads, these normal subjects demonstrated a markedly greater response in ∆PcritA–P and ∆PA–P compared with sleep apnea patients who had comparable levels of mechanical loads (passive Pcrit; see Fig. 3B). This finding suggests that neuromuscular responses to airway obstruction improve airway patency during sleep and offset mechanical loads in normal subjects. The present study suggests that increased mechanical loads and blunted neuromuscular responses are both required for the development of obstructive sleep apnea.

Our approach to studying the upper airway during sleep is based on a Starling resistor model in which upper airway patency is determined primarily by the critical pharyngeal pressure (44, 54). The critical pressure has previously been shown to describe a continuum of pharyngeal collapsibility from health to varying degrees of upper airway obstruction including snoring, hypopneas, and apneas (11, 57). As summarized in Fig. 3, in normal sleeping subjects with intact neuromuscular responses, the active Pcrit is markedly negative and the upper airway remains patent compared with obstructive sleep apnea patients in whom the Pcrit is close to atmospheric pressure and the upper airway occludes spontaneously at sleep onset. Furthermore, a range of critical pressures can be obtained that is characterized by a relative threshold above which recurrent apneas and hypopneas begin to occur (apnea-hypopnea threshold; see Fig. 5) (11). The present study confirmed that an active Pcrit greater than approximately −5 cmH2O distinguished most obstructive sleep apnea patients (14 of 16 subjects) from normal subjects (15 of 16 subjects) (11).

In the present study, the passive Pcrit was higher than the apnea-hypopnea threshold in all sleep apnea patients, indicating the presence of increased mechanical loads as previously reported (3, 22, 43, 54, 67). Moreover, the passive Pcrit measurements were comparable to previous values obtained under conditions of minimal or absent neuromuscular tone, suggesting that mechanical loads are similar during the sleep state and anesthesia (5, 6, 20). Elevations in passive Pcrit observed in apneic patients compared with normal subjects cannot be attributed to overt anthropometric differences between the groups since our groups were matched for age, sex, and obesity. Furthermore, subjects with obvious alterations known to increase mechanical loads were excluded (e.g., tonsillar hypertrophy, microagnathia) (39, 66). Nevertheless, subtle structural changes (29, 51) or differences in regional adiposity (16, 38, 61) could explain elevations in upper airway mechanical loads.

A major finding in the present study was the observation that normal subjects could be divided into two subgroups based on the passive Pcrit. Half of the normal subjects demonstrated a passive Pcrit that was below the apnea-hypopnea threshold of −5 cmH2O, which was sufficient to maintain upper airway patency, regardless of their ability to further lower their critical pressure during the active state. In the remaining normal subjects, the passive Pcrit was greater than −5 cmH2O, placing them at risk for obstructive sleep apnea (see Fig. 5). Nevertheless, these normal subjects compensated for increases in mechanical loads by increasing airflow over a wide range of PNS (∆PA–P) during the active condition and by lowering the active Pcrit below the apnea-hypopnea threshold (increased ∆PcritA–P). In contrast, obstructive sleep apnea patients failed to compensate for the increased mechanical loads by lowering their Pcrit during the active state and demonstrated reduced ∆PA–P and ∆PcritA–P responses, suggesting the presence of blunted neuromuscular responses. It is unlikely that blunted neuromuscular responses in sleep apnea patients were due to...
baseline differences in mechanical loads between the normal and sleep apnea groups because $\Delta P_{\text{A-P}}$ and $\Delta P_{\text{critA-P}}$ remained low in sleep apnea subjects after matching both groups for the level of mechanical loads (see passive $P_{\text{crit}}$, Fig. 3B). The finding suggests that nonmechanical factors, i.e., neuromuscular factors, most likely account for the differences in the $\Delta P_{\text{A-P}}$ and $\Delta P_{\text{critA-P}}$ between the two groups.

The mechanism for the lack of $\Delta P_{\text{A-P}}$ and $\Delta P_{\text{critA-P}}$ responses in obstructive sleep apnea patients is unclear. Recent evidence suggests that neuromuscular responses account for approximately two-thirds of the variability in sleep apnea severity (69), suggesting that compensatory neuromechanical mechanisms account for active responses to upper airway obstruction and play a dominant role in preventing upper airway collapse during sleep. As the upper airway collapses during sleep, an integrated compensatory neuromuscular response can maintain airway patency, as reflected by decreases in the active $P_{\text{crit}}$. Several mechanisms might account for blunted dynamic responses to airflow obstruction in apneic patients. First, a loss of pharyngeal mechanoreceptors input (1, 23, 28) may result from chronic exposure to upper airway obstruction and mucosal inflammation. Second, neuromuscular activity may be inadequate or waking neuromuscular reflex responses are lost during sleep (17, 36, 37, 48, 68). Third, decreases in ventilatory response to hypercapnia and hypoxemia in sleep apnea patients (10, 14, 27, 42) indicate insensitivity of central chemoreflex pathways that predispose to recurrent airway collapse. Fourth, instability in the chemical control system, as reflected by measurements of loop gain, has been observed in specific strata of sleep apnea patients, which may contribute to recurrent airway obstruction (22, 41, 67, 71).

Recently, it has been suggested that hyperventilation following arousals during sleep may also contribute to upper airway collapse and destabilize breathing patterns due to altered loop gain (21, 70). In the present study, we demonstrated that periodic breathing began at comparable levels of upper airway obstruction in both normal and sleep apnea subjects, indicating a similar propensity for periodic breathing. Moreover, the experimental findings in normal subjects indicate that if the upstream pressure is lowered sufficiently, the normal dynamic neuromuscular responses can be overwhelmed, leading to periodic obstructive hypopneas and apneas, as would occur spontaneously in obstructive sleep apnea patients (11, 24).

In a limited number of sleep apnea patients and normal subjects, we monitored $EMG_{GG}$ activity to document the presence of neuromuscular activation. Although $EMG_{GG}$ activity increased in the active compared with the passive state in both groups, neither tonic nor peak phasic between-group differences were observed, and no relationship between measures of $EMG_{GG}$ activity and $\Delta P_{\text{critA-P}}$ or $\Delta P_{\text{A-P}}$ was identified in either group. There are several potential explanations for why $EMG_{GG}$ responses did not differ between the two groups and did not correlate with $\Delta P_{\text{critA-P}}$ or $\Delta P_{\text{A-P}}$. First, the genioglossus muscle is only one of many muscles controlling pharyngeal patency and may not represent composite neuromuscular responses to airflow obstruction. Second, we only monitored EMG activity in approximately one-third of our subjects and may have inadequate power to discern differences in neuromuscular responses. Third, it is possible that neuromuscular and airflow responses to upper airway obstruction may be dissociated (54), suggesting that the genioglossus activity may reflect rather than control the state of pharyngeal patency (8, 30, 31). Finally, the conversion of electrical activity to pharyngeal muscle pressure may be impaired in sleep apnea patients and could account for the lack of difference in $EMG_{GG}$ between normal and sleep apnea subjects despite differences in dynamic airflow responses.

Our study has several limitations. First, our passive upper airway state represents a hypotonic upper airway rather than anatomic airway. Nevertheless, our passive $P_{\text{crit}}$ measurements in both normal and sleep apnea subjects are comparable to those reported under the anatomic condition (5, 6, 20). Second, recurrent obstructive apneas and hypopneas in the active condition were associated with sleep-wake instability, which might have confounded the active response. Nevertheless, our active $P_{\text{crit}}$ measurements were made under comparable conditions of NREM sleep in both groups, who exhibited similar susceptibility to (Vmax at the transition threshold) (57, 63). Furthermore, evidence for activation was observed over the entire active pressure-flow relationship, regardless of whether sleep and breathing patterns were stable ($\Delta P_{\text{A-P}}$) or not stable ($\Delta P_{\text{critA-P}}$). Third, while subjects were carefully matched for anthropometric and demographic characteristics, it is possible that differences in body fat distribution (16, 38, 61) and/or hormonal status (7, 40, 45, 72) may account for differences in passive and/or active $P_{\text{crit}}$ between groups.

The major implication of the present study is that defects in both upper airway mechanical (passive $P_{\text{crit}}$) and neuromuscular control ($\Delta P_{\text{critA-P}}$ or $\Delta P_{\text{A-P}}$) must be present to develop obstructive sleep apnea (Fig. 5). If the mechanical loads on the upper airway result in a passive $P_{\text{crit}}$ that is greater than approximately $-5$ cmH2O, obstructive sleep apnea will occur if the individual is unable to adequately recruit neuromuscular responses ($\Delta P_{\text{critA-P}}$ or $\Delta P_{\text{A-P}}$) and lower the active $P_{\text{crit}}$ to below the $-5$ cmH2O threshold. In contrast, if the mechanical loads result in a passive $P_{\text{crit}}$ of less than approximately $-5$ cmH2O, obstructive sleep apnea will not occur, regardless of the neuromuscular responses ($\Delta P_{\text{critA-P}}$ or $\Delta P_{\text{A-P}}$) recruited to further lower the active $P_{\text{crit}}$. Thus we propose a “two-hit” hypothesis, where defects in both upper airway mechanical and neuromuscular control are necessary for the development of obstructive sleep apnea.

The precise factors causing these mechanical and neuromuscular defects, however, remain undefined. For example, it is known that weight loss leads to substantial decreases in the active $P_{\text{crit}}$ (53), which account for improvements in sleep apnea severity (62). Nevertheless, it is unclear whether improvements in upper airway function with weight loss are due to mechanical or neuromuscular factors. Given the increasing prevalence of obesity in Western society, a substantial proportion of the general population may be at risk for developing obstructive sleep apnea (73). Our findings lead us to speculate that obesity leads to defects in mechanical and neuromuscular control of upper airway function. In future studies, partitioning of upper airway collapsibility into its mechanical and neuromuscular components could serve to examine the therapeutic effects of pharmacological agents, upper airway surgery, oral appliance devices, and weight loss on upper airway collapsibility and as intermediate physiological traits for studies examining the genetic susceptibility to obstructive sleep apnea.
REFERENCES


