Obstructive sleep apnea is an important disorder because of both its prevalence and its cardiovascular and neurocognitive sequelae. Despite the fact that male sex is a major risk factor for this disorder, the mechanisms underlying this predisposition are unclear. To understand the pathophysiologic basis of the male predisposition for pharyngeal collapse, we performed a detailed analysis of the anatomic and physiologic features of the upper airway in a cohort of normal and near-normal subjects (equal number of men and women). Although no important physiologic (genioglossal electromyogram, airflow resistance) differences were observed between sexes, a number of anatomic differences were apparent. The pharyngeal airway length was substantially longer in men compared with women. There was also an increased cross-sectional area of the soft palate and an increased airway volume in men compared with women. Using signal-averaged anatomic data from male and female subjects, we developed representative male and female finite element airway models. This model demonstrated the male airway to be substantially more collapsible than the female airway, solely on the basis of anatomic differences. This study suggests that the male predisposition to pharyngeal collapse is anatomically based, primarily as a result of an increased length of vulnerable airway as well as increased soft palate size.

Keywords: apnea; finite element; length; sleep; upper airway

Obstructive sleep apnea (OSA) is a common disorder characterized by abnormalities in pharyngeal anatomy and physiology (1). The associated repetitive pharyngeal collapse during sleep has important, well-established neurocognitive and cardiovascular sequelae (2–9). In theory, male sex, a major risk factor for OSA, could predispose to pharyngeal collapse secondary to sex-based differences in pharyngeal anatomy and/or physiology.

A major hypothesis regarding collapse of the upper airway during sleep is predicated on the fact that affected individuals have compromised pharyngeal airway anatomy (10–14). However, through local reflex-driven neuromuscular compensatory mechanisms, individuals with OSA have increased pharyngeal dilator muscle activation during wakefulness, preventing collapse of the vulnerable pharyngeal airway (15). With the onset of sleep, however, these protective reflexes are lost, leading to a fall in dilator muscle activation and collapse of the airway (16–18). Therefore, upper airway anatomy and pharyngeal dilator muscle activation are both involved in pharyngeal collapse.

In theory, male sex could potentially be associated with differences in bony configuration, fat deposition, or soft tissue structure (i.e., anatomy), making the upper airway more vulnerable to collapse. Similarly, male sex could compromise pharyngeal dilator muscle activation or control, leading to an increased propensity for pharyngeal collapse. Finally, sex differences in ventilatory control stability (loop gain), if present, could explain some of the predisposition of men to OSA as well.

Although a number of studies have addressed the issue of sex predisposition to pharyngeal collapse, no clear explanation has emerged (19–38). Although subjects with apnea have a reduced pharyngeal lumen size when compared with normal subjects, the bulk of the literature suggests that women actually have a smaller pharyngeal lumen size than men (even when normalized for body size) and thus in theory should have more apnea. Regarding muscle performance, one report suggests increased pharyngeal dilator muscle activation in women during wakefulness when compared with men, although this has not been a consistent finding (21, 26). In addition, no data are currently available regarding sex differences in muscle responsiveness to standard stimuli such as negative pressure. Finally, although differences in ventilatory control may be important in apnea pathogenesis, only one group has reported a relatively subtle difference in the Pco2 apnea threshold during sleep between normal men and women (36). Thus, the mechanisms whereby male sex increases the susceptibility to pharyngeal collapse are unclear. As a result, in this study we combined assessments of upper airway anatomy and physiology in normal and near-normal males and females in an attempt to explain the male predisposition to pharyngeal collapse.

In the present studies undertaken, we recognized the potential inability of physiologic assessments to specifically define the impact of anatomic variability. Multiple subtle differences in airway anatomy could all contribute to a more collapsible airway in men than women, yet we could have little ability to sort out the relative importance of each variable. To address this potential problem we are developing a biomechanical model of the human upper airway to assess the isolated effect of specific anatomic features on pharyngeal physiologic function. The finite element method is a widely accepted numeric procedure for obtaining solutions to many of the problems encountered in engineering analyses when an analytic solution cannot be developed (39, 40).

The purpose of this study was twofold: (1) to determine...
Standard overnight polysomnography. Sleep was monitored for a majority of these studies were conducted with thermistors alone. A total of 19 male and 20 female subjects were group-matched subjects. Although we consider our population to have minimal or no sleep apnea, none of the subjects in this study would meet the criteria for For our model, we described the upper airway as a two-dimensional element model of the human upper airway. Using this model to assess the impact of specific anatomic features on upper airway mechanics, we attempted to determine the mechanism(s) underlying the male predisposition to pharyngeal collapse.

**METHODS**

**Anatomy and Physiology**

**Subjects.** A total of 19 male and 20 female subjects were group-matched for both age and body mass index. All subjects were normal, as determined on the basis of a thorough history and physical examination, and were free of any symptoms suggesting sleep apnea, other sleep disorders, or other relevant medical conditions. None were taking any medication. Further subject characteristics are provided in Table 1. The subjects were recruited from the general population through e-mail advertisements and poster bulletins. Before participation, all provided informed consent for the protocol, which had the prior approval of the Human Subjects Committee of the Brigham and Women's Hospital (Boston, MA).

**Equipment and Procedures**

*Standard overnight polysomnography.* Sleep was monitored for a minimum of 7 hours and staged by electroencephalogram, electromyogram (EMG), electro-oculogram, nasal and oral airflow (thermistors), nasal pressure (Validyne pressure transducer; Validyne, Northridge, CA), chest plus abdominal wall motion (piezoelectrodes), electrocardiogram, anterior tibialis EMG, and arterial oxygen saturation (BCI Capnograph, Waukesha, WI). Apneas and hypopneas were scored by a blinded registered sleep technician using American Academy of Sleep Medicine (41, 42) criteria. We prespecified an apnea–hypopnea index cutoff of 15 events per hour to define the presence or absence of obstructive and/or central sleep apnea. The relatively high apnea–hypopnea index threshold was chosen because of our use of the nasal pressure signal, which tends to increase the number of events scored when compared with thermistors alone (43). Although some data suggest important adverse effects of OSA in the range of 5–15 events per hour of sleep, the majority of these studies were conducted with thermistors alone. Although we consider our population to have minimal or no sleep apnea, none of the subjects in this study would meet the criteria for the sleep apnea syndrome (i.e., symptoms).

*Magnetic resonance imaging.* All images were obtained on the same 1.5-T MR scanner (Signa Advantage; GE Medical Systems, Waukesha, WI). Subjects were studied in the supine posture with the head secured in the neutral anatomic position (Frankfort plane). Sequential T1-weighted axial images were obtained from the top of the hard palate to the vocal cords. Sagittal T1-weighted images were also obtained. We examined, using slight modifications of previously defined techniques (12, 13, 44), the following:

Minimal axial airway image (see Figure E1 in the online data supplement): airway cross-sectional area, anteroposterior and lateral widths of the airway, tissue analysis including thickness of the lateral pharyngeal walls, intramandibular width, thickness of the pharyngeal fat pads, pterygoid muscle thickness, skeletal anteroposterior (mandible to vertebrae) and lateral (intramandibular) distances, and skeletal area.

Axial anatomy: using computer-aided three-dimensional segmentation of the images, volumetric analyses were performed to calculate the volume of the pharyngeal airway between the hard palate and base of the epiglottis and the volume within the rigid skeleton between the mandible and vertebrae.

*Sagittal anatomy* (see Figure E2 in the online data supplement): the soft palate area, soft palate length, pharyngeal length (measured from the hard palate to the base of the epiglottis), tongue height, tongue width, and tongue area were defined.

Once imaging was complete, the images were then transferred to a UNIX-based SUN Station, where they were processed, analyzed, and interpreted. A “connection machine” (edge detection algorithm using simple thresholding) was used to avoid subjective bias in measurement. Upper airway physiology. The physiologic techniques employed are as previously described, and are detailed in the online data supplement. The subjects were studied during basal breathing and with negative pressure stimulation during wakefulness. Output from intramuscular genioglossus EMG electrodes and Millar pressure catheters was recorded during basal breathing and negative pressure pulses (45–47).

*Protocol.* Each subject underwent each of the three parts of the study (polysomnography, MRI, and upper airway physiology) on separate days.

*Statistics.* For the sex comparisons, unpaired t tests were used for normally distributed data, and Wilcoxon rank tests (nonparametric) were used for nonnormally distributed results. All results are presented as means ± standard error of the mean, with p < 0.05 being the threshold for statistical significance. As multiple (14) anatomic variables are presented, the possibility exists that significant differences will be found due to chance alone. To address this, a Bonferroni correction yielded a p value of 0.004 as the threshold for significance, accounting for multiple comparisons. Thus, this was used as our standard for statistical significance. For measurements where a significant difference was observed, we also normalized the variable of interest for multiple measures of body size, so as to ensure that the observed differences were not simply a surrogate for body size; however, in all cases, this normalization did not affect the results.

**Finite Element Model**

For our model, we described the upper airway as a two-dimensional channel in the midsagittal plane. This allowed the simulation of tongue and uvula movements in the anteroposterior direction, which maintains features important in negative pressure-induced upper airway collapse. The geometric structure, which includes the tongue, mandible, hard palate, soft palate, uvula, hyoid bone, epiglottis, and pharyngeal airway,
In the structure depicted in Figure 1, the hard palate, mandible, and the bottom of the epiglottis are fixed. The tongue and uvula, except the parts connecting directly to the fixed boundaries, can move freely under loads. Fluid–solid interaction conditions are given at the deformable front wall of the upper airway, which is composed of three interfaces (air–uvula, air–tongue, and air–epiglottis). The posterior pharyngeal wall is modeled as a rigid structure, allowing little deformation because of the vertebral bodies. The pressures at the entrance and the exit of the upper airway are provided in each case. The simulation used a physiologic direction for airflow (primarily laminar, fully developed), yielding a more negative pressure at the epiglottis during inspiration than at the caonae. The governing equations controlling air flow and tissue deformation are solved under these boundary conditions, using the finite element method. This simulation is performed with nonlinear dynamic analysis software (ADINA 7.3; ADINA R&D, Watertown, MA). Eight node rectangular solid elements and three node triangular fluid elements are employed.

From the airway deformation patterns predicted using this model at different pharyngeal negative pressures, one can measure the dimensional changes at desired areas in the upper airway, in particular the narrowest part of the airway just above the tip of the uvula. We defined $D_{\text{max}}$ as the dimension of the narrowest part of the pharynx as measured in the anteroposterior direction of the pharyngeal airway in the midsagittal plane. Further, we defined $S_{\text{max}}$ by the area of the retropalatal airway. Specifically, we measured total pharyngeal length (from hard palate to epiglottis) and determined a point above the uvula whose distance was 20% of total pharyngeal length from the caudal tip of the uvula. $S_{\text{max}}$ is then the projected area of the portion of the velopharynx in the midsagittal plane extending from the caudal tip of the uvula, up cranially a distance of 20% of the total pharyngeal length.

**RESULTS**

**Anatomy and Physiology**

Complete data sets were obtained for all participants except one subject, who did not complete the MRI scanning. From the MRI data, several strong sex-related differences emerged (Figures 2 and 3, Table 2). First, the pharyngeal airway length was considerably greater in men than in women (see Figure 4). This difference persisted even when the data were normalized for body size using multiple normalization strategies including body height. Second, men had a significantly greater soft palate cross-sectional size when compared with women. This difference persisted after normalizing for several measures of body size, including body surface area. Because it is unclear which is the best technique for normalizing anatomic variables for body size, and moreover, because it is unclear whether normalization is even appropriate, we have reported both the raw results for variables of interest, as well as the normalized values for variables that were significantly different. Finally, the size of the pharyngeal airway lumen was greater in men than in women. This finding was true for airway area (axial images) and airway volume (multiple axial images), and persisted after normalizing for airway length, body size, and other variables. Conversely, no important sex-related differences in parapharyngeal fat distribution were observed.

To assess the reliability of our measurements, we conducted a blinded assessment of the airway length of 10 randomly chosen individuals on 10 separate occasions. On the basis of these data, we calculated a reliability coefficient of 97%.

From the detailed physiologic assessments, no sex-based differences were observed (see Table E1 in the online data supplement). Men and women in the present study were equivalent in terms of baseline genioglossus activation (tonic, phasic, and peak phasic activity as a percentage of maximum activity), pharyngeal resistance, and negative pressure genioglossus reflex responsiveness. These data support no important physiologic differences in upper airway mechanics or muscle activation/responsiveness of normal (and near-normal) men as compared with normal (and near-normal) women during wakefulness.
Finite Element Model

For the finite element model, we focused on two areas. First, we simply created male and female upper airways based on the data from 10 subjects (5 male, 5 female) as described in METHODS. We then tested the relative collapsibility of the two models under simulated sleeping (some muscle activity) and simulated passive (no muscle activity) conditions as described. Second, as the airway lengths were so strikingly different between men and women, we determined, using our model, the isolated effect of airway length on pharyngeal collapsibility.

The “sleeping” male and female airway models are shown in Figures E4a and E4b, respectively (see the online data supplement), when −13 cm H₂O was applied to the pharynx. This pressure, as modeled on the basis of the data of Schwartz and coworkers, completely collapsed the male airway, but not the female airway. The female airway required −18.5 cm H₂O to collapse completely. Figure E3 in the online data supplement shows the detailed deformations at different negative pressures (0, −2, −5, −7, −10, and −13 cm H₂O) for both men (Figure E4a) and women (Figure E4b). As can be seen, as the pharyngeal pressure becomes more negative, the tongue and uvula collapse toward the posterior pharyngeal wall. However, at each negative pressure, the collapse of the female airway is less than is seen in the male. When the male upper airway fully collapses at −13 cm H₂O, the female airway is still patent. The female airway demonstrated a significantly lower closing pressure, −18.5 cm H₂O, implying less collapsibility. Table 3 (Sleeping conditions) shows the predicted decreases in Dₘₘ, the dimension of the narrowest part of pharynx, and Sₜₜ, the area of a portion of velopharynx on the middle sagittal plane (see METHODS). Dₘₘ decreases by 13.3 to 100% for men and by 7.5 to 65% for women, whereas Sₜₜ decreases by 9.7 to 82% for men and by 8.4 to 59.5% for women, when the pressure drops from −2 to −13 cm H₂O. Again, −18.5 cm H₂O was required to completely collapse the female airway.

The passive pharyngeal airway model (simulated no dilator muscle activity) behaves similarly, as shown in Table 3 (Passive conditions). When the pressure drops from −2 to −5 cm H₂O, Dₘₘ decreases by 33.3 to 100% for men and by 22.5 to 62.5% for women, whereas Sₜₜ decreases by 26.4 to 82% for men and by 20.1 to 56.7% for women. Again, there is a substantial difference in closing pressure, −5 cm H₂O for men and −7 cm H₂O for women.

We also assessed the isolated influence of pharyngeal airway length on upper airway collapsibility. This was accomplished by

---

**TABLE 2. EXPERIMENTAL RESULTS: MAGNETIC RESONANCE IMAGING**

<table>
<thead>
<tr>
<th>Image</th>
<th>Anatomic Feature</th>
<th>Value</th>
<th>SEM</th>
<th>Value</th>
<th>SEM</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagittal</td>
<td>Centerline length, mm</td>
<td>50</td>
<td>1.2</td>
<td>44.5</td>
<td>1.2</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>Tongue AP at midpoint, mm</td>
<td>60.6</td>
<td>1.3</td>
<td>62.8</td>
<td>1.7</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Tongue height, mm</td>
<td>67.4</td>
<td>1.1</td>
<td>62</td>
<td>1.3</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>Airway area, mm²</td>
<td>949.3</td>
<td>66.6</td>
<td>666.9</td>
<td>54.2</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>Airway length, mm</td>
<td>76.1</td>
<td>1.6</td>
<td>58.2</td>
<td>1.9</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td></td>
<td>Airway length/ht, mm/cm</td>
<td>0.43</td>
<td>0.01</td>
<td>0.36</td>
<td>0.01</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td></td>
<td>Soft palate area, mm²</td>
<td>476.9</td>
<td>30.5</td>
<td>324.9</td>
<td>18.8</td>
<td>0.0004</td>
</tr>
<tr>
<td></td>
<td>Soft palate area/body surface area, mm²</td>
<td>249.1</td>
<td>18.2</td>
<td>187.2</td>
<td>12.5</td>
<td>0.01</td>
</tr>
<tr>
<td>Axial</td>
<td>Airway, anteroposterior/lateral</td>
<td>0.39</td>
<td>0.04</td>
<td>0.49</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>Lateral walls, mm</td>
<td>25</td>
<td>2.8</td>
<td>27.1</td>
<td>1.6</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>Fat pad thickness, mm</td>
<td>22.9</td>
<td>3</td>
<td>19.3</td>
<td>1.8</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Fat pad area, mm²</td>
<td>248.4</td>
<td>42</td>
<td>250.7</td>
<td>32.6</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Pterygoid muscle, mm</td>
<td>26</td>
<td>1.6</td>
<td>30</td>
<td>1.9</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Airway volume, mm³</td>
<td>13,086.1</td>
<td>1,115.6</td>
<td>7,276.6</td>
<td>765.1</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

*Definition of abbreviations: AP = anteroposterior; Ht = height.*
comparing the male “sleeping” airway model with an otherwise identical model changed by only a 30% decrease in airway length. We chose this value of 30% as this was approximately the difference observed between the two sexes in our experimental measurements of pharyngeal airway length. Table 3 (Length changes) shows the changes in D_{min} and S_{a} when the male pharyngeal airway length is decreased by 30%. As can be seen, the closing pressure for the shorter airway is considerably more negative, falling from −13 to −19 cm H\textsubscript{2}O. As can be seen in Table 3 (Length changes), all measures of collapsibility decrease when the shorter airway is compared with a larger airway. These differences are similar to those observed between the male and female models.

DISCUSSION

The results of this study suggest that at least one plausible explanation for the male predisposition to pharyngeal collapse is sex-based differences in upper airway anatomy. When compared with women, men had increased pharyngeal airway length, increased soft palate area, and increased pharyngeal volume. On the other hand, no consistent sex-related differences in upper airway physiology were observed during wakefulness. Specifically, there were no systematic differences in pharyngeal dilator muscle activation/responsiveness, or pharyngeal mechanics. The finite element method also improves our understanding of upper airway biomechanics. The observed sex-related differences in pharyngeal anatomy had an important impact on the vulnerability of the upper airway to collapse. The average male airway was substantially more collapsible than the average female airway based purely on anatomic features, with differences in airway length being the most important variable.

Although the longer pharyngeal airway length in men compared with women has not been reported, these observations are consistent with previous literature in this area (19). Several cephalometric and morphometric variables that have been associated with OSA (such as facial length and caudal hyoid position) may be surrogates for pharyngeal airway length (51–56). In addition, at least one study suggests that airway length may impact pharyngeal collapsibility as well. The fact that the male airway is longer, even when length in normalized for body height, suggests that the observed length differences are sex-specific rather than a function of men being taller than women. In theory, a greater length of susceptible airway (hard palate to epiglottis) would increase the propensity for pharyngeal collapse if all other variables are held equal (57). Therefore, for a given negative airway pressure during inspiration, the extent of pharyngeal collapse would be greater in men than in women, simply on the basis of anatomic differences.

We have reported increased pharyngeal collapse in men as compared with women during nonrapid eye movement sleep in response to inspiratory resistive loading (21). In this prior study, the development of inspiratory flow limitation was substantially more common in men than in women after load application during nonrapid eye movement sleep. However, no important differences in pharyngeal dilator muscle activation (phasic and tonic) were observed. We therefore concluded that the sex differences in upper airway collapsibility must be related to differences in either anatomy and/or tissue characteristics (e.g., compliance, deformability). However, one publication reported no important differences between the sexes regarding critical closing pressure during sleep (31). We have no clear explanation for these discordant results. Because the upper airway responds differently when suction is applied from the nose as opposed to the trachea (collapse versus flow limitation), one could argue that the response to inspiratory resistive loading is a more physiologic perturbation than is an assessment of critical closing pressure. In addition, the manipulations in pharyngeal pressure that occur during a critical closing pressure determination may significantly influence the activity of the pharyngeal dilator muscles. The current study would suggest that the observed anatomic differences may be adequate to explain the greater collapsibility, although we cannot exclude additional differences in tissue characteristics. However, further work is clearly needed in this area, particularly with regard to potential sex differences in tissue elastic modulus.

An increased size of the soft palate was also observed in men when compared with women. This finding was true for both the centerline length and the cross-sectional area of the soft palate on the midsagittal plane. This finding persisted even after normalizing for differences in body surface area, suggesting that...
they are sex-specific and not just a function of body size. The relevance of this increase in soft palate tissue in men compared with women is unclear on the basis of the anatomic data alone.

No consistent differences in upper airway physiology/muscle activation were observed between the sexes in the present study. This is in direct contrast to the work of Popovic and White, who previously reported an increased genioglossal EMG in awake women when compared with men (26). The explanation for the discrepant results is unclear, although several additional studies from our laboratory have failed to find sex-based differences in muscle activation (21). Whether this relates to technique (computerized versus paper-based data acquisition), altitude of experiment, sample size, or other variables is unclear at this time.

The lack of difference between the sexes in genioglossal responsivity to negative pressure is also noteworthy. We have reported that upper airway dilator muscle activation is primarily driven by subatmospheric pharyngeal pressure on a moment-by-moment basis during inspiration (45, 46, 59, 60). Therefore, we believe that the increase in pharyngeal dilator activation observed in response to the potentially collapsing airway pressure is protective of pharyngeal patency (61, 62). The fact that men and women behaved identically in this regard suggests that the female advantage in the maintenance of pharyngeal patency is not mediated through this protective reflex.

Differences in upper airway resistance have also been observed between sexes in previous studies, but this has not been a universal finding. The most thorough study performed to date measured pharyngeal resistance in both sexes during wakefulness and nonrapid eye movement sleep (33). Only during slow-wave sleep did clear sex differences in airflow resistance emerge. Therefore, in our study sample, the finding of comparable upper airway resistance in men and women is consistent with most of the reported literature (34).

We believe our finite element model is and will continue to be an important technique for understanding upper airway physiology. It allowed us to build anatomically correct sagittal models of the human upper airway. This is in direct contrast to the work of Popovic and White, who previously reported that upper airway dilator muscle activation is primarily driven by subatmospheric pharyngeal pressure on a moment-by-moment basis during inspiration (45, 46, 59, 60). Therefore, we believe that the increase in pharyngeal dilator activation observed in response to the potentially collapsing airway pressure is protective of pharyngeal patency (61, 62). The fact that men and women behaved identically in this regard suggests that the female advantage in the maintenance of pharyngeal patency is not mediated through this protective reflex.

Differences in upper airway resistance have also been observed between sexes in previous studies, but this has not been a universal finding. The most thorough study performed to date measured pharyngeal resistance in both sexes during wakefulness and nonrapid eye movement sleep (33). Only during slow-wave sleep did clear sex differences in airflow resistance emerge. Therefore, in our study sample, the finding of comparable upper airway resistance in men and women is consistent with most of the reported literature (34).

We believe our finite element model is and will continue to be an important technique for understanding upper airway physiology. It allowed us to build anatomically correct sagittal pharyngeal airways, apply properties to the tissues on the basis of previous investigations, and then assess collapsibility at pressures commonly encountered in the human upper airway. The result was a substantially more collapsible male airway with differences in airway length being the largest determinant. Although we accept that this model required some assumptions, we believe the current model provides useful, physiologically accurate information regarding the variables addressed.

This study has a number of limitations. First, the anatomy and physiology studies were performed during wakefulness. One could argue that because our desire was to improve our understanding of OSA, that the study of normal and near-normal subjects during wakefulness potentially says little about disease. However, there have been clearly documented abnormalities of upper airway anatomy and physiology in subjects with apnea compared with control subjects documented during wakefulness. Sleep-enhancing techniques to facilitate image acquisition such as sleep deprivation and/or benzodiazepines may, however, influence pharyngeal mechanics/muscle activation, confounding data interpretation (63–65). We therefore believe that careful anatomic/physiologic assessment during wakefulness does provide valuable information. Second, the methodology for between-subject comparison of electromyographic recordings has been questioned. The method of measuring genioglossal EMG as a
percentage of maximum activity does have some variability based on needle placement, individual differences in anatomy, subject effort, and other variables. We have previously observed this measurement to be reproducible and to demonstrate clear differences between subjects with apnea and normal control subjects (15). We therefore believe it to be valid and useful. Furthermore, no superior technique has been reported to date. Third, one could argue that our MRI measurements are potentially subjective and therefore susceptible to bias. To avoid this problem, we used edge detection software and strictly prespecified objective clearly definable landmarks when appropriate.

When measurement decisions were questionable, a blinded radiologist who was naive to the goals of the study was consulted. In addition, we and others (19, 58) have shown good reproducibility with these types of anatomic measurements, as is illustrated by the high reliability coefficient observed in the present study and previous studies from our radiology group using similar techniques (66–68). Fourth, one could argue that multiple comparisons were made in our studies and that significant differences were observed simply on the basis of chance alone. However, even using the strictest correction for multiple comparisons, the observed anatomic differences remained significant. Finally, as stated previously, the finite element model required a number of assumptions, including two dimensions, laminar flow, and isotropic and nondeformable tissues. However, we believe that the errors introduced by these assumptions introduce minimal bias into the model and that the results obtained with this model are consistent with common clinical observations. Moreover, despite making a number of assumptions, marked differences between sexes in upper airway collapsibility were observed. Therefore, the finite element model emphasizes the biomechanical importance of these anatomic variables.

This study suggests that there are clearly definable differences in upper airway anatomy between men and women, with little to no difference in muscle activation/control. Furthermore, on the basis of computational modeling, we believe that the anatomic differences observed can significantly impact airway collapsibility and may, in part, explain the male predisposition to OSA.

References
