A new nasal acoustic reflection technique to estimate pharyngeal cross-sectional area during sleep

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Huang, J., N. Itai, T. Hoshiba, T. Fukunaga, K. Yamanouchi, H. Toga, K. Takahashi, and N. Ohya. A new nasal acoustic reflection technique to estimate pharyngeal cross-sectional area during sleep. J Appl Physiol 88: 1457–1466, 2000.—The conventional acoustic reflection technique in which acoustic waves are launched through the mouth cannot be applied during sleep, nor can it be applied to the nasopharynx, which is the major site of occlusion in patients with obstructive sleep apnea syndrome. We propose a new technique of nasal acoustic reflection to measure pharyngeal cross-sectional areas including the nasopharynx. The acoustic waves are introduced simultaneously to both nostrils during spontaneous nasal breathing. A new algorithm takes into account the nasal septum with asymmetric nasal cavities on both sides and assumes prior knowledge of the cross-sectional area of the nasal cavities and the position of the nasal septum. This method was tested on an airway model with a septum and on healthy human subjects. The conventional technique gave inaccurate measurements for pharyngeal cross-sectional areas for an airway model with asymmetric branching, whereas the new technique measured them almost perfectly. The oro- and hypopharyngeal cross-sectional area measurements acquired by the new method were not different from those obtained by the conventional method in normal subjects. This new method can be used as a monitor of upper airway dimensions in nocturnal polysomnography.

acoustic reflection technique; nasopharynx; sleep apnea

ACOUSTIC REFLECTION TECHNIQUE has been employed to assess the pharyngeal, tracheal, and bronchial cross-sectional areas along the airway (2, 5, 12). This method has been used extensively, particularly for the comparative assessment of pharynx size among snorers, non-snorers, and patients with obstructive sleep apnea syndrome (3, 4, 10). It has the advantage of being noninvasive and quick, and it also allows for continuous evaluation of the patency of these regions. However, the technique has two major restrictions: it cannot be used during sleep and it cannot assess the nasopharynx. In this technique, in which acoustic waves are launched to the airway via the mouth, subjects are requested to breathe wholly through the mouth without wearing a nose clip. This controlled and deliberate breathing method is required to ensure complete closure of the uvula to the posterior wall of the nasopharynx and, thereby, to preclude acoustic waves transmitting to the nasal pathway (15). Otherwise, the pharyngeal cross-sectional area beyond the uvula would be distorted by the component of the reflected waves from the nasal pathway. Therefore, this technique has never been applied during sleep when nasal breathing dominates.

Although this technique has also been applied to the nasal cavity by introducing acoustic waves via one nostril (7–9), the measurement was limited to the point of the choana, beyond which acoustic waves separate to the nasopharynx and the opposite side of the nasal cavity, and, hence, the pharyngeal cross-sectional area cannot be obtained for the reason described above. The nasopharyngeal cross-sectional area would be measured under the condition that acoustic waves enter both nostrils simultaneously, and both nasal cavities are assumed to be symmetric. This is because a symmetric branching and encountering of acoustic waves in nasal cavities would measure the correct nasopharyngeal cross-sectional area as if the septum did not exist. However, this is generally not the case. Furthermore, the areas of both nasal cavities temporarily change in an asymmetric way. Therefore, the existing nasal acoustic reflection technique is not applicable to the pharynx, including the nasopharynx.

We propose a new algorithm to overcome the difficulties described above. After developing reflection and transmission formulas of acoustic waves at the beginning and ending points of the nasal septum, we combined them with the former Ware and Aki algorithm (17). Acoustic waves were launched simultaneously to both nostrils via a nasal adapter during spontaneous
from the first discontinuity of the cross-sectional area \(v_A\), with unit amplitude initially propagates to the right at algorithms. Suppose that an impulsive acoustic wave the new one, to look at the relationship between the two substituting some parts of the conventional one with those of intuitive way: first, by precisely depicting a generalized acoustic method and can be written as

\[
y = \frac{A}{\rho c}
\]

where \(\rho\) is the density of the gas, \(c\) is the velocity of sound propagation, and \(A\) is the cross-sectional area of each section. This model is different from that of Jackson et al. (12) in the branching portion, which includes both the nasal septum and a nasal adapter. The formulas of the reflection and transmission of acoustic waves at the sections without branching are the same as before, even in the nasal cavities. Therefore, the only problems we have to formulate are those at the beginning and ending points of the branching. The derivation of formulas at these points are presented in the APPENDIX.

Here, we describe the new algorithm in a rather intuitive way: first, by precisely depicting a generalized step of the conventional algorithm and, next, by substituting some parts of the conventional one with those of the new one, to look at the relationship between the two algorithms. Suppose that an impulsive acoustic wave with unit amplitude initially propagates to the right at the microphone position. After one sampled time interval, \(\tau = 2\pi c/\lambda\), by observing the first reflected wave, \(R_0\), from the first discontinuity of the cross-sectional area between \(y_0\) and \(y_1\), we can calculate \(y_1\) and thereby \(A_1\) from the following equation and Eq. 1

\[
y_1 = \frac{(1 - r_0)/(1 + r_0)}{y_0}
\]

where \(r_0\) is the reflection coefficient at the discontinuity, and equals \(R_0\). In the same way, from \(R_1\) we can calculate \(y_2\) and \(A_2\). Next, \(R_2\) contains not only the primary wave (thick line with arrow in Fig. 1) but also the secondary wave (thin line with arrow), which is the multiple reflected wave at the discontinuity between \(y_1\) and \(y_2\). Because we can calculate the secondary wave from already known parameters, \(y_0\), \(y_1\), and \(y_2\), and by subtracting it from \(R_2\), we can separate the primary component in it, from which we can derive \(y_3\).

The secondary wave in the \(n\)th reflected wave at the microphone position, \(R_n\), can be systematically calculated with the known parameters \(y_0\), \(y_1\), \(y_2\), \(y_3\), and hence we can derive the primary wave and the next unknown admittance \(y_{n+1}\). The procedure to calculate the secondary wave can be generalized as shown in Fig. 2. First, the incidental \((p_i^1)\) and the reflected \((p_{r1})\) waves at the discontinuity between \(y_{n-1}\) and \(y_n\) at the \((n-1)\)th step, and the incidental waves \((p_{i1}^1, p_{i2}^1, \ldots)\) and the reflected waves \((p_{r1}^1, p_{r2}^1, \ldots)\) at each discontinuity at the \((n-2)\)th step are already known. Next, the secondary waves at the first mesh point denoted by \(a\) in the \((n-1)\)th step, \(p_{a1}^2\) and \(p_{a2}^2\), are calculated by using \(p_{i1}^1\) and \(p_{r1}^1\) as shown in Fig. 3A. With the use of this newly calculated \(p_{a1}^2\) and the known \(p_{i2}^2\), the waves at the next mesh point \(b\) are calculated as \(p_{b1}^2\) and \(p_{b2}^2\). Thus all the secondary waves in the \((n-1)\)th step are given by successive calculation at each mesh point in the reverse direction toward the microphone position. Third, the secondary waves at the \(n\)th step can be obtained by the same process as the \((n-1)\)th step, successively calculating the mesh points \(a\), \(b\), \(c\), . . . Finally, we get the secondary wave at the microphone position and the primary wave by subtracting it from \(R_n\).
In contrast, each mesh point has the same structure as in Fig. 3A in the Ware and Aki algorithm (17), and in the new algorithm one of four different structures of Fig. 3, A–D, should be selected, depending on the position of the mesh point, i.e., prebranching or postbranching point, the starting, the middle, and the ending point of the septum. To see how parameters inferred in each step are linked together in the new algorithm, suppose that we are inferring for the postbranching position, the pharyngeal region, as the nth step in Fig. 2. In the tour of the mesh points, to calculate the secondary waves the first mesh point of a' is of the Fig. 3A type, and, therefore, the same procedure as the Ware and Aki algorithm continues until the ending point of the nasal septum, the choana. Then the structure type should be substituted with that of Fig. 3D. Here, at the discontinuity between sections \( y_s \) and \( y_{s+1} \) (where \( s \) is ending), the backward-traveling pressure wave separately transmits to both nasal cavities from the choana, and also the forward-traveling wave from the left (right) nasal cavity separately transmits to the nasopharynx and to the opposite nasal cavity. Because these incidental waves to this mesh point (1 backward and 2 forward waves) and the transmission and reflection coefficients at the discontinuity are already known, the three transmitting waves to the pharynx and both nasal cavities can be calculated (see APPENDIX). For the next several mesh points, the Fig. 3C type structure is used in the nasal cavity. Here the waves independently transmit in both nasal cavities, and, therefore, the Ware and Aki algorithm can be employed in each nasal cavity. When the tour of the mesh point reaches the starting point of the septum, the discontinuity between sections \( y_{s-1} \) and \( y_s \) (where \( s \) is starting), where the Fig. 3B type structure is used, the forward-traveling pressure wave wave transmits separately to both sides of the septum, and, in the same way, the backward-traveling wave from the left (right) side of the septum transmits separately toward the microphone and to the opposite side of the septum. Because these incidental waves to this mesh point (1 forward and 2 backward waves) and the transmission and reflection coefficients at the discontinuity are already known, the three transmitted waves can be calculated (see APPENDIX). After this mesh point, the tour meets the Fig. 3A type structure until the microphone position and the Ware and Aki algorithm can be employed again. Eventually we get the secondary wave at the microphone position and the primary wave by subtracting it from \( R_n \) to get the unknown admittance \( y_{n+1} \).

Prior Knowledge of the Cross-Sectional Area in Both Nasal Cavities and the Position of the Nasal Septum

When the inferring points are in the septum, including the starting and the ending points, the algorithm should be modified from the one just described above because there are two unknown admittances in this step. First, we consider the inference of the starting point of the septum. Before this point, the Ware and Aki algorithm (17) can be employed. When the acoustic wave first arrives at this point, the discontinuity between \( y_{s-1} \) and \( y_s \) in Fig. 1, the Ware and Aki algorithm gives the sum of both branched areas at section \( s \) from the primary wave component of \( R_{s-1} \) (see APPENDIX). Here, we presuppose that the area profile of the left nasal cavity and thus \( y_{sL}, y_{s+1L}, \ldots, y_{sL} \) (where \( L \) is left) are known beforehand, as described at the end of this section. Then we can calculate \( y_{sR} \) by subtraction and hence \( A_{sR} \) (where \( R \) is right).

Next, to infer the middle points in the right nasal cavity, we used the following procedure. The incidental waves to both branches are initially the same as shown in the APPENDIX. Then we can calculate the primary waves as well as the secondary waves beforehand in the left nasal cavity (dashed line with arrow in Fig. 1). Therefore, we can get the primary waves from the discontinuities of the right nasal cavity by subtracting not only the secondary waves but also the primary waves in the left nasal cavity from \( R_{sR}, R_{s+1R}, \ldots, R_{s-1R} \). From there we get \( A_{s+1R}, A_{s+2R}, \ldots, A_{sR} \).

Finally, for the inference of the next section to the ending point of the septum, \( y_{e-1} \), we no longer know a priori the primary wave from the left nasal cavity. Therefore, a special procedure is needed to get the unknown admittance \( y_{e-1} \), which is presented in the APPENDIX. This was done by obtaining an equation of the primary wave component in \( R_n \) in Fig. 1 and finding a solution for \( y_{e+1} \).

The cross-sectional areas of one nasal cavity, \( A_{sL}, A_{s+1L}, \ldots, A_{sR} \) were measured by the conventional nasal acoustic reflection technique by introducing acous-
Acoustic waves through one nostril, while closing one of two passages of a nasal adapter at the starting point of branching (see below). Because the cross-sectional area abruptly decreased at this point of unilateral closing and because of the limitation of the resolving power in the acoustic method, the areas determined in this way were overestimated after the portion of abrupt change. Consequently, the other side of the nasal cavity also was underestimated at the corresponding regions, and thereby the estimation of the pharyngeal cross-sectional area was impaired. Because the overestimation ceased in approximately three sections, which are within the region of the nasal adapter, and both nasal passages of the adapter were made symmetric in shape, we substituted the first three sections, \(A_{1L}, A_{2L},\) and \(A_{3L}\) with one-half of the corresponding cross-sectional areas measured by introducing acoustic waves through both passages.

**METHODS**

**Apparatus**

Because the fundamental apparatus for the acoustic reflection technique is the same as that for the conventional one, we will limit our explanation to a brief description of our apparatus. It consists of a wave tube with a length of 4 m and an inner diameter of 1.6 cm, a horn driver located in its midpoint (ID60; University Sound, Buchanan, MI), and a semiconductor pressure transducer to measure the incidental and reflected acoustic waves (XCW-190; Kulite Semiconductor, Levittown, NY). The length of the tube could probably be shortened considerably if the inference is limited up to the pharyngeal cross-sectional areas, because the distance to the pharynx is rather short. Because there is a great deal of dead space in the equipment, we used a bias flow to avoid interfering with the subject's breathing. The transducer for the acoustic waves was positioned at a distance of 25 cm from the end of the tube and flush with the inside wall. For measurements in both the supine position and the sitting position, we joined an additional 33-cm-long curved tube to the end of the wave tube. In the conventional acoustic reflection technique, we used a commercialized mouthpiece, which was attached to the wave tube. In the measurement of the nasal acoustic reflection technique, we used a custom-made nasal adapter to connect the apparatus and the subject's nostrils. The adapter consists of three pieces, one of which was made of acrylate and was severed by a lathe to give a precise dimension. The nasal and the pharyngeal models were securely joined to each other and connected directly to the wave tube. Data from these models were compared with data from the conventional method without branching and those from the conventional method with branching.

**Human Study**

Subjects. Five healthy male subjects were recruited from our laboratory. They ranged in age from 25 to 47 yr and in body mass index \([\text{weight (kg)/height}^2\text{(m)}]\) from 22.5 to 27.5 (Table 1). Their pharyngeal cross-sectional areas both in the sitting and supine positions determined by the two methods were compared. All subjects gave their informed consent to the study protocol.

Analysis of pharyngeal cross-sectional area. Figure 4 shows a typical example of airway cross-sectional area vs. distance functions comparing the two methods in one subject. After recognizing the narrowest portion in around \(-7\text{ to }-9\text{ cm from teeth as the fauces and that in around }\sim 18\text{ to }20\text{ cm as the glottis in the data by the conventional method, we defined a region between 2 cm distal to the fauces and 2 cm proximal to the glottis as the pharyngeal segment and calculated the mean pharyngeal cross-sectional area. The corresponding pharyngeal cross-sectional area by the nasal method was also obtained. The distance in the nasal pathway from the nostril to the glottis was }\sim 3\text{ cm longer than that from the teeth to the glottis from observation with a bronchoscope. We corrected for the difference of the site of the pharyngeal segment in the area vs. distance functions between the two methods. Measurement of the length of the nasal septum. The algorithm requires a prior knowledge of the position of the ending point of branching, the choana. We determined it by an acoustic method, by introducing an impulsive acoustic wave to one nostril, measuring the incidental wave and the transmitted wave to the other nostril, and multiplying one-half of the propagation time between the two nostrils by the speed of sound.**

**Table 1. Anthropometric data**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Gender</th>
<th>Age, yr</th>
<th>Height, cm</th>
<th>Weight, kg</th>
<th>Smoking, pack·yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF</td>
<td>M</td>
<td>25</td>
<td>171.3</td>
<td>56.5</td>
<td>0</td>
</tr>
<tr>
<td>MK</td>
<td>M</td>
<td>27</td>
<td>172.0</td>
<td>67.0</td>
<td>0</td>
</tr>
<tr>
<td>JH</td>
<td>M</td>
<td>47</td>
<td>167.0</td>
<td>68.0</td>
<td>7.5*</td>
</tr>
<tr>
<td>KU</td>
<td>M</td>
<td>27</td>
<td>166.0</td>
<td>60.0</td>
<td>8.0</td>
</tr>
<tr>
<td>TT</td>
<td>M</td>
<td>31</td>
<td>164.0</td>
<td>63.0</td>
<td>13.5*</td>
</tr>
</tbody>
</table>

Protocol. Because many prior studies reported the accuracy of the pharyngeal and the tracheal cross-sectional areas determined by the conventional method, we compared the data from the new method with those from the conventional method. Data were obtained in both the sitting and the supine positions. The jaw position was carefully observed, and efforts were made to keep it as similar as possible in each body posture in the two methods. To determine the cross-sectional area of one nasal cavity earlier in the measurement with the new method, one of two pieces inserted into the nostrils of the nasal adapter was closed with sealing material at the starting point of the branching. After the cross-sectional area in either nasal cavity was measured in this way, acoustic waves were simultaneously introduced to both nostrils.

Statistical analysis. We used a paired t-test to test differences in the data for the conventional method and those for the new technique. The level of statistical significance used was $P < 0.05$.

RESULTS

Model

Figure 5A shows inferred cross-sectional area vs. distance functions for the first model, the septum of which branches with equal cross-sectional areas (dashed line). Comparison with the conventional algorithm (dotted line) disclosed perfect coincidence in the pharyngeal region, showing the validity of the new algorithm. These data also agree well with the inferred pharyngeal areas in a model without septum (solid line), which is the consequence of symmetric branching as described in the APPENDIX.

For the second model, in which the cross-sectional areas at the sides of the septum are different but constant (reflectionless condition), the two algorithms gave identical pharyngeal cross-sectional areas (Fig. 5B). These data also agree with that in a model without septum, which confirms the theory (see APPENDIX).

In the third model with asymmetric branching, the conventional acoustic reflection technique gave inaccurate cross-sectional areas, whereas the new technique recovered them almost perfectly (Fig. 6).

Human

Figure 7 shows a comparison of the cross-sectional areas between the new and the conventional method in a subject (JH), who induced asymmetric branching in the nasal septum with unilateral decongestion. Here, as in the model study described above, the same acoustic waves were used between the new and the conventional methods. When the nasal cavity was almost symmetric before decongestion, there were few differences in the pharyngeal cross-sectional areas obtained by the two methods (Fig. 7A). On the other hand, when the left nasal cavity was decongested and enlarged with two sprays of 60 µg of tetrahydrozoline hydrochloride, the two methods derived significant
differences in the cross-sectional areas of the nasal cavity and the pharynx, showing the influence of asymmetric branching (Fig. 7B).

Figure 8 shows a comparison of oro- and hypopharyngeal cross-sectional areas between the new and the conventional method in the sitting or supine position. In this instance, the acoustic waves were introduced through the mouth in the conventional method vs. through both nostrils in the new method. Oro- and hypopharyngeal cross-sectional areas did not differ between the two methods in either position and decreased in the supine position compared with the sitting position.

**DISCUSSION**

To date, the acoustic reflection technique has never been applied to the assessment of the upper airway dimensions during sleep. Sleep apnea or sleep-related disordered breathing only occurs during sleep; therefore, the new technique may provide a strong tool for extracting information about the pathogenesis of the upper airway, which cannot be obtained by measurements taken in a patient who is awake.

As shown by the model data, both this and the conventional methods accurately measured the simulated pharyngeal cross-sectional areas following the symmetrically branched septum (Fig. 5). In the case of asymmetrically branched septum, however, only this new method correctly recovered the pharyngeal cross-sectional areas (Fig. 6). As demonstrated in the differences between the two methods in the human study (Fig. 7), the conventional method will give impaired data when acoustic waves are simultaneously introduced to both nostrils and both nasal cavities are quite different from each other, especially in the region near the choana.

To study the accuracy of this method, we compared the oro- and hypopharyngeal cross-sectional areas inferred by this and the conventional methods, with acoustic waves introduced through the nose in the former and through the mouth in the latter. The rationale of this comparison is that these pharyngeal regions are capable of being inferred by both methods and that the accuracy by the conventional method in these regions has already been established by several authors (5, 13). The pharyngeal cross-sectional areas did not vary between the methods, as expected. Furthermore, the measurements in both methods decreased with the postural change from the sitting to the supine position, as reported (6). We believe that the accuracy is also preserved in the nasopharyngeal cross-sectional areas because, if that were not so, the accuracy of further distances, i.e., oro- and hypopharynx, would not be preserved either. However, further studies, including comparisons with magnetic resonance-computerized tomography, are needed to confirm this because this pharyngeal region has not previously been inferred by the acoustic reflection technique.

**Methodological Problems**

Although the new technique seems to be fairly reliable, some problems must be considered. First, the paranasal sinuses may influence the data because they form additional parallel pathways (branches) in the nasal cavity. Hilberg and Pedersen (9) investigated the influence of the maxillary sinuses on estimated nasal cross-sectional areas, which were determined by acoustic waves introduced from one nostril. They estimated the size of the ostium of the maxillary sinus in normal subjects to be ~3–8 mm in diameter when the nasal cavity was decongested by xylometazoline, and the tongue pushed up the soft palate and narrowed the corresponding nasal pathway.
sinus overestimated the cross-sectional areas in the posterior part of the nasal cavity and epipharynx. However, they also showed that the wider the ostium, the greater the overestimation, and, when not decongested, the degree of overestimation was rather small. We believe that the influence of this factor on our data is minimal because, except for Fig. 7, we did not use any decongesting agents and there were no differences in the oro- and hypopharyngeal cross-sectional areas between this and the conventional methods.

Fig. 7. Human study with an almost symmetric or asymmetric branching at the nasal cavity in a subject (JH). A: condition when both sides of the nasal cavity are almost symmetric. Bottom: solid and dashed lines show cross-sectional areas of left and right side of the nasal cavity, respectively. Abscissa shows distance from the nostril, i.e., the negative distance represents the portion of the nasal adapter, and the positive distance nasal cavity. Each area vs. distance function is mean value of 50 measurements during normal nasal breathing. Top: cross-sectional areas represented by new (solid line) and conventional method (dashed line) were almost identical. For cross-sectional areas in the branching portion including the nasal cavity and the nasal adapter (between 2 vertical lines), we depicted the sum of the cross-sectional areas of both sides at corresponding distances. B: when the left nasal cavity is unilaterally decongested, cross-sectional areas of both nasal cavities showed a marked asymmetric configuration (bottom). Top: cross-sectional areas in the nasal cavity and the pharynx were significantly different between the 2 methods.

Fig. 8. Comparison of pharyngeal cross-sectional areas between this (nose) and the conventional (mouth) methods in healthy male subjects (mean ± SE, n = 5). There were no differences between the 2 methods either in the sitting or supine positions. In both methods, pharyngeal cross-sectional area decreased in the supine position. NS, not significant.

Fig. 9. Nasopharyngeal cross-sectional areas in a 47-yr-old male subject. Fifty area vs. distance functions were superimposed on each panel. A: subject breathed nasally at first and then switched to mouth breathing. Cross-sectional areas of the nasopharynx decreased, reflecting the velum closure to the nasal pathway. B: subject breathed nasally with a slight opening of his mouth at first and then pushed the soft palate with his tongue. Cross-sectional areas of the nasopharynx decreased, while the more distant airways remained unchanged.
Another source of error could arise from the accuracy of the position and the length of the nasal septum. As shown in Fig. 1, we assumed that the septum starts and ends at distances of an integer multiple of the short segment from the microphone position, i.e., s and e + 1 multiple, respectively. We obtained the septum length from the independent measurement of the transmission time of acoustic waves between the two nostrils and divided it by the length of the segment, 0.7 cm, to get the integer multiple. Therefore, any error of the septum position would be 0.35 cm at most. This magnitude of error was not considered to be important because the resolving power of the cross-sectional area was ~3 cm in the distance axis in this study with the use of air as a test gas. The model results demonstrated this assertion, i.e., despite the fact that we did not adjust the length or the position of the models, the estimated data almost exactly recovered the actual measurements. To further verify this, we examined the influence of an additional error of one integer multiple of the septum position, i.e., another 0.7-cm error. The difference between estimations was noticeable but not excessive (data not shown). This confirms the above argument that the truncation of the septum position to integer multiple does not produce a significant influence on the estimation.

Third, we assumed in this new algorithm that both nasal cavities communicated to the nasopharynx, although they were asymmetric. However, one or both nasal cavities can be closed or extremely narrow. The attenuation of sound is large in this case, and the algorithm would not work well. This problem remains to be solved.

Applications

There are many fields in which this method can be applied. First, it can be used as a monitor of the pharyngeal and airway cross-sectional areas in nocturnal polysomnography, detecting the site of closure of the upper airway in patients with obstructive sleep apnea syndrome. To this end, endoscopy and magnetic resonance imaging have been used (1, 11, 16). Because the former is too invasive to be placed in the pharynx all night and the latter is too expensive to apply to all patients and too noisy to allow natural sleep, these methods have not been used as a monitor and have been limited to use for research purposes. Therefore, this method can be the first for monitoring the pharyngeal and airway dimensions during sleep.

The method can be also used as a monitor of airway choking in newborn babies. With application in children and infants, increase of the sampling frequency to 100 kHz may improve the resolution to 1.7 mm, provided the scaling of the equipment and the frequency characteristics of the microphone are adequate. It can also be a convenient method of measuring the nasopharyngeal cross-sectional areas. To our knowledge, this is the first method for this purpose other than well-established imaging techniques, such as computed tomography, using X-ray or magnetic resonance.

Future Directions

In this study, we assumed that subjects breathed through the nose during sleep. Although this is normally true, they may breathe through both the nose and mouth simultaneously. Because acoustic waves introduced from both nostrils split to the hypopharynx and mouthward at the uvula in this situation, the estimation fails for distances beyond the nasopharynx for the reason described in the introduction. Even in this circumstance, however, the method is valid for the nasopharyngeal cross-sectional areas. The method could be modified to overcome this obstacle by introducing acoustic waves not only from the nostrils but also from the mouth and taking into account an additional branching in the mouth.

It is not comfortable for subjects to sleep through the night using the method described here because head and neck positions are fixed with the equipment. The technique should be improved by a reduction in the size of the equipment and in the nasal adapter. A two-microphone method, rather than a single-microphone method, can reduce the size substantially (14). A special nasal mask not requiring insertion of any materials into the nostrils should be developed to introduce the acoustic waves.

In this study, we presented a new acoustic reflection technique that enabled us to assess the size and function of the pharynx during sleep. This is also the first method using the acoustic reflection technique to measure the nasopharynx. Long-term continuous use of this equipment as a monitor would more extensively clarify the physiological and/or pathophysiological condition of the upper airway.

APPENDIX

Sound Transmission at the Beginning and Ending Points of the Septum

At the starting point of the septum, there are three waves into this point: one forward- and two backward-traveling waves, as shown in Fig. 3B. We separately formulated these waves and then combined them based on the principle of the superposition. First, we consider a wave traveling to the right into the beginning of the branching as shown in Fig. 10A (a

![Fig. 10. Reflection and transmission of an incidental wave from the left (A), a reflected wave from the right to the starting point of the septum (B), and acoustic waves at the ending point of the septum (C). Subscript t, transmitted. See text for details.](http://jap.physiology.org/download/)
forward traveling wave \( p_r \)). The continuity conditions of pressure and volume flow at the boundary are as follows

\[
p_1 + p_r = p_R = p_L
\]

\[
p_i - p_{s-1} = p_R \cdot y_{s-1} + p_L \cdot y_s
\]

where \( p_i, p_r, p_R, \) and \( p_L \) are the incidental, reflected, and transmitted acoustic pressure waves to the right and left branches, respectively. From these, the reflection coefficient \( (r) \) and the transmission coefficient \( (t) \) at the boundary are given as follows

\[
r_{s-1} = \frac{p_r}{p_i} = \frac{(y_{s-1} - y_s) / (y_{s-1} + y_s)}{1 + r_{s-1} - 2y_{s-1} / (y_{s-1} + y_s)} \quad (A3)
\]

\[
t_{s-1} = \frac{p_R}{p_i} = \frac{p_R / p_L / p_i}{1 + r_{s-1} - 2y_{s-1} / (y_{s-1} + y_s)} \quad (A4)
\]

where \( y_s = y_R + y_L \), which corresponds to the sum of the cross-sectional areas in the right and the left branches at section \( s \). Equation A4 expresses that transmitted waves in both branches are the same, i.e., the same pressure waves begin to transmit to both branches irrespective of the difference in their cross-sectional areas.

Hence, if there is physical similarity between the structures of both branches, or if the cross-sectional area of each branch remained unchanged (reflectionless condition), the waves in both branches are identical at the same distances and behave as if they did not branch. It is only under these conditions and when the acoustic waves are simultaneously introduced to both nostrils that the nasal septum does not affect the estimated pharyngeal cross-sectional areas by the conventional acoustic reflection technique. In the typical case, in which branching at the septum is symmetric, a marked influence on the pharyngeal area by the existing method was demonstrated (Figs. 6 and 7).

When a wave traveling to the left in the right branch (reversed direction) comes back to the same branching point as shown in Fig. 10B (a backward-traveling wave \( p_R^R \)), the reflection \( (r_{s-1,R}) \) and the transmission coefficient \( (t_{s-1,R}) \) are, in the same way as in Eqs. A3 and A4, given as follows

\[
p_{R}^R / p_{i}^R = -r_{s-1,R} = \frac{(y_{sR} - (y_{sL} + y_{sL-1})) / (y_{sR} + y_{sL} + y_{sL-1})}{1 - r_{s-1,R}}
\]

\[
p_{i} / p_{i}^R = \frac{p_{i} / p_{R}^R}{1 - r_{s-1,R}}
\]

where \( y_s = y_{sR} + y_{sL} \), \( y_{s-1} = y_{sL-1} \), and \( 1 - r_{s-1} \) is the transmission coefficient for a forward-traveling wave \( (t) \) and \( 1 + r_{s-1} \) respectively, at the ith discontinuity, those for a backward-traveling wave are \( -r_i \) and \( 1 - r_i \) in the conventional algorithm.

For a wave traveling to the left in the left branch (a backward-traveling wave \( p_i^L \)), those coefficients are as follows

\[
p_{R}^L / p_{i}^L = -r_{s-1,L} = \frac{(y_{sL} - (y_{sR} + y_{sL-1})) / (y_{sL} + y_{sR} + y_{sL-1})}{1 - r_{s-1,L}}
\]

By the principle of superposition, the resultant waves are the sum of those waves. Finally, the formulas for the ending point of the septum are the same as those described above and are not presented here.

An Estimation Method of \( y_{e+1} \)

A procedure to infer \( y_{e+1} \), the next section to the ending point of the septum, consists of obtaining an equation of the primary wave in \( R_e \) in Fig. 1 and rearranging it to calculate \( y_{e+1} \). Two primary waves transmitted to the ending point of the septum in both branches, \( T_{eL} \) and \( T_{eR} \), are written as follows (Fig. 10C)

\[
T_{eL} = \Pi_t \Pi_{tL} (i = 0, 1, \ldots, s - 1; j = s, s + 1, \ldots, e - 1)
\]

\[
T_{eR} = \Pi_t \Pi_{tR} (i = 0, 1, \ldots, s - 1; j = s, s + 1, \ldots, e - 1)
\]

where \( t \) is the transmission coefficient at the discontinuities from the microphone position to the starting point of the septum, \( t_{sL} \) and \( t_{sR} \) are those in each nasal cavity, and these are known parameters. Then we can write the two reflected waves, \( L \) and \( R \), from the discontinuity between \( y_s \) and \( y_{e+1} \) as follows

\[
L = r_{el} T_{eL}^+ + (1 + r_{el}) T_{eR}^+
\]

\[
R = (1 + r_{el}) T_{eL}^- + r_{er} T_{eR}^-
\]

These sum up to the primary wave component of \( R_e \) in Fig. 1 as

\[
\text{Prim}(R_e) = LT_{eL}^- + RT_{eR}^-
\]

where

\[
T_{eL}^- = \Pi_t ({-t}) \Pi_t ({-t}_{sL}) \quad (i = 0, 1, \ldots, s - 2; j = s - 1, s, \ldots, e - 1)
\]

The negative sign of \( t_{sL}, t_{sR} \), and \( t_{eR} \) denotes the corresponding transmission coefficients for the backward-traveling waves at each discontinuity. Rearranging Eq. A15 yields the admittance \( y_{e+1} \)

\[
y_{e+1} = \left[ y_{sL} (\gamma - T_{eL}^{-} - T_{eR}^{+}) + y_{sR} (\gamma - T_{eL}^{-} + T_{eR}^{+}) \right] / \left[ y_{sL} + T_{eL}^{-} + T_{eR}^{+} \right]
\]

where

\[
\gamma = [\text{Prim}(R_e) - T_{eL}^+ T_{eR}^- - T_{eR}^+ T_{eL}^-] / (T_{eL}^- + T_{eR}^-)
\]

The primary wave component in \( R_e \) was obtained by subtracting the secondary component in it, and then the unknown admittance \( y_{e+1} \) was calculated by Eq. A18.

This work was supported by a grant for Collaborative Research from Kanazawa Medical University (C96–9, C98–2). The FORTRAN source program is available. Please write to J. Huang.
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Received 12 February 1998; accepted in final form 23 November 1999.

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