An upper airway resonator model of high-frequency inspiratory sounds in children with sleep-disordered breathing

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Rembold, Christopher M., and Paul M. Suratt. An upper airway resonator model of high-frequency inspiratory sounds in children with sleep-disordered breathing. J Appl Physiol 98: 1855–1861, 2005. First published December 23, 2004; doi:10.1152/japplphysiol.01231.2004.—The goal of this study was to determine how high-frequency inspiratory sounds (HFIS) are generated by sleeping children with obstructive sleep-disordered breathing (OSDB). We hypothesized that HFIS are generated when a high-velocity jet of air, generated by a narrowed upper airway, induces the upper airway to act as a resonating chamber. We tested two predictions of this hypothesis: 1) the upper airway is narrowed in children who make HFIS and 2) the length of the upper airway, calculated from HFIS harmonic intervals, is similar to that calculated from magnetic resonance imaging (MRI) scans. The study was conducted in the setting of a sleep laboratory. Participants included 29 children between 6 and 12 yr of age with adenotonsillar hypertrophy suspected of having OSDB. Minimum cross-sectional airway area and airway long dimensions (lips to larynx or soft palate) were measured in awake children with MRIs. Later that night, sound was recorded with a microphone suspended above their bed while the children underwent polysomnography. Sounds were later analyzed with fast Fourier transforms. We found that sleeping children who generated HFIS had significantly narrower upper airways compared with children who did not make HFIS [minimum airway area 20.5 ± 4.4 vs. 70.9 ± 22.5 mm2 (mean ± SE), respectively; P = 0.02]. There was a significant inverse correlation between the log10 of the narrowest airway area and the number of HFIS recorded per hour (r2 = 0.55, P < 0.00001). The harmonics characteristics of HFIS predicted that they were generated by sound resonating in chamber whose length was 12.0 ± 0.9 cm, which is similar to the MRI measured distance from the lips to the larynx of 12.8 ± 0.4 cm. In conclusion, these data suggest that children generate HFIS when 1) they have a narrowed upper airway and 2) their upper airway acts as a resonating chamber.

Habitual snoring in children is associated with poor school performance (6, 15), neurobehavioral deficits (10), and the attention deficit hyperactivity disorder (3, 4). Information about habitual snoring is generally subjective and obtained by parental report (6, 15), neurobehavioral deficits (10), and the attention deficit hyperactivity disorder. We defined a HFIS as an inspiratory sound associated with a single inspiration that has discrete harmonics with frequencies >2,000 Hz, i.e., increased sound intensity at several high-pitched frequen-

tics. HFIS differ from what is commonly called snoring in adults, which is characterized by snoring frequencies typically <1,000 Hz (11, 12). HFIS in children with OSDB can occur in isolated breaths, but they typically occur in consecutive breaths with occasional runs exceeding 100. Children who made more HFIS had more OSDB, as evidenced by higher obstructive apnea-hypopnea indexes. Children with adenotonsillar hypertrophy made more HFIS than children whose tonsils and adenoids had been removed.

The mechanism of HFIS generation in children with OSDB is unknown. The goal of this study was to test the general hypothesis that HFIS are generated when a high-velocity jet of air, generated by a narrowed upper airway, induces the upper airway to act as a resonating chamber. To understand the tests of this hypothesis, it is important to review the physics of sound resonance in a cylindrical pipe (for this paragraph, see Ref. 13). When the air in a pipe is excited, e.g., by blowing into a flute, the air in the flute resonates in proportion to the length of the pipe. In a pipe with two open ends, the lowest resonant frequency occurs when vibration is maximal at both ends and there is a single node (i.e., a location with no vibration) midway between the ends, i.e., half of a full wave. This lowest resonant frequency of the open-ended pipe is called the fundamental frequency or first formant frequency (F1). The open-ended pipe typically produces a series of formant frequencies, termed harmonics, at integer multiples of F1, which represent vibrations with additional nodes, e.g., F2 is twice the frequency and has two nodes (a full wave), F3 is three times the frequency and has three nodes (one and a half full waves). Thus an open-ended pipe can generate a series of harmonics at integer multiples of the lowest harmonic, i.e., “even” harmonics. The length of the open-ended pipe (L) acting as a resonating chamber can be calculated from F1 and the speed of sound (343 m/s at sea level). The equation is L (in m) = speed of sound/2F1 (the 2 corrects for the half wave), which simplifies to L (in cm) = 17,150/F1. When a pipe is closed at one end, the closed end creates a node and the open end vibrates, so the lowest harmonic is one-quarter of a full wave. Therefore, the equation for the length of the pipe closed at one end is L (in m) = speed of sound/4F1, which simplifies to L (in cm) = 8,575/F1. For the closed-end pipe, additional resonances are odd integral multiples representing additional nodes, e.g., F2 is three times the frequency and has two nodes (three-quarters of a full wave), F3 is five times the frequency and has three nodes (five-quarters of a full wave). Therefore, a closed-ended pipe will generate a series of harmonics at odd integer multiples of...
the lowest harmonic, i.e., “odd” harmonics. The higher harmonics of simple cylindrical pipes tend to have less amplitude (loudness) than the lower harmonics. More complex tubes, like the upper airway, will have selective amplification of some harmonics on the basis of the characteristics of the resonance chamber.

Our hypothesis is that HFIS are generated when a high velocity jet of air, generated by a narrowed upper airway, induces the upper airway to act as a resonating chamber. There are three testable predictions of this hypothesis: 1) the upper airway should be narrowed in children who make HFIS, 2) the length of the upper airway calculated from HFIS harmonic intervals should be similar to that measured from magnetic resonance imaging (MRI) scans of the upper airway, and 3) children who make HFIS should create a high-velocity jet of air during inspiration. In this report, we tested the first two of these three predictions. We compared the upper airway cross-sectional area in children who made HFIS and those who did not. We also calculated the length of the resonating chamber from the harmonic intervals of HFIS and compared this length with the measured length of their upper airways.

METHODS

A model for generating HFIS. To produce a high-velocity air jet analogous to inspiration through a narrowed airway, we attached a small-diameter tube (3 mm ID, 2.5 cm long) to a vacuum source. The vacuum pressure was adjustable, and its level was measured with a water manometer attached to the vacuum line via a T connection. This air jet was inserted into a series of cylindrical pipes where it could excite the air in the pipe to vibrate and produce resonant sounds. Cylindrical resonant chambers (pipes) were commercial white polyvinyl chloride water pipes: inner diameter of 2.54 cm, a wall thickness of 3 mm, and cut to lengths of 4, 6, 12, 16, and 32 cm. All sound recordings with this model were made at a distance of 1 m from the recording microphone. The air jet was moved in and out of the plastic pipes and one of the author’s oral cavity as described in RESULTS.

Subjects. All participants were volunteers who signed informed consent and whose parents signed informed consent for the study. The University of Virginia Human Investigation Committee approved these studies. We studied children between the ages of 6 and 12 yr of age with adenotonsillar hypertrophy who were suspected of having OSDB. These children were consecutive participants in a larger study on the effect of OSDB due to adenotonsillar hypertrophy on behavior, cognitive, performance and growth. Because subjects in this larger study had to hold still for 5 min in an MRI scanner, subjects <6 yr old were not included in the larger study. The larger study involved studying subjects both before and 6–12 mo after an adenotonsillectomy. The decision whether to perform an adenotonsillectomy was made by the children’s physicians.

We selected 29 children from the larger study because they had 1) sound recordings to detect HFIS and 2) upper airway MRIs of sufficient quality to make the measurements detailed below. Specifically, there were a total of 48 consecutive sound recordings in 39 children. Nine children were recorded twice, once before and once after adenotonsillectomy; only their first study was included in this analysis. Ten studies were not included because children were unable to hold still long enough in the MRI scanner to obtain acceptable motion-free images. Twenty-one of the 29 subjects were part of our prior study that first characterized HFIS (12). These subjects from the prior study were included in the present study because we were testing different hypotheses.

Sleep studies and sound recording. All subjects had overnight polysomnography using conventional techniques including electroencephalograms, electrooculograms, submental electromyograms, nasal airflow measured with a nasal cannula attached to a pressure transducer, oral airflow measured with a thermistor, pulse oximetry, and chest and abdominal movement detected by respiratory inductance plethysmography as previously described (12). During polysomnography, sounds were recorded from a microphone suspended 1.2 m above the bed. Sounds were sampled and digitally stored at 44,000 Hz for 4 h, which generated 1.3 gigabytes of data. The sounds were later analyzed with fast Fourier transforms (FFTs) at 0.1-s intervals for frequencies between 0 and 10,000 Hz at 100-Hz intervals. FFTs were displayed as “spectrographs” (See Fig. 1 in prior paper (12) and also in http://www.people.virginia.edu/~ps4p/HFIS) with the colors black (level 0 sound), dark blue (level 2), light blue (level 3), yellow (level 4), red (level 5), and white (level 6) representing low to high sound intensities. Sounds were considered to be HFIS if they met both of the following criteria: 1) they had one or more discrete frequency bands over 2,000 Hz (sound intensity greater than −135 dB) and 2) they occurred during inspiration as determined by the nasal flow and the chest/abdominal movement signals. We counted the number of individual HFIS occurring during the entire 4-h recording period and for analysis expressed it as number of HFIS per hour of sleep. We also determined the maximal amplitude of HFIS occurring with each patient (on the 0–6 scale noted above). A snoring questionnaire (SnoreQ) was administered to all parents to solicit information about snoring (2). Parents were asked to describe their children’s snoring as occurring as follows: 1, never; 2, rarely (less than once month); 3, occasionally (1–4 times a month); 4, frequently (more than once a week); or 5, most nights.

MRI. MRI scans were obtained on the children while awake on the same day as their polysomnography. MRI was performed with a 1.5-T superconducting magnet and a head coil (Magneton VISION, Siemens Medical Systems, Iselin, NJ). After a longitudinal relaxation time-weighted sagittal scout image, a sagittal turbo spin-echo sequence with an effective echo time/repetition time of 99/4,000 ms, 11 echoes per shot, and a fat saturation pulse were obtained. The field of view was 250 × 250 mm², with a matrix of 242 × 256, resulting in a pixel size of ~0.94 × 0.94 mm. Slice thickness was 3 mm, and slices were contiguous sections obtained from the region of the adenoids through the larynx with the plane perpendicular to the posterior airway wall. Two acquisitions were obtained. The study was repeated in the axial direction with a field of view of 175 × 200 mm². Measurements on the MRI scans were performed by using MedX software (Medical Numerics, Sterling, VA). We measured the curvilinear length of the upper airway from the lips to the inferior portion of the soft palate and from the lips to the larynx on a midline sagittal image. We also measured the airway cross-sectional area on sequential images from the adenoids to the larynx that were three-dimen-sional reconstructions perpendicular to the long axis of the upper airway. We then selected the narrowest portion of the area for comparisons.

Statistical analysis. After the sound recordings were analyzed for HFIS, results were compared with the results of standard polysomnography analyzed over the same time interval and results from MRI scans. Data was analyzed by SigmaPlot (SPSS) for regression analysis or Sigmastat (SPSS) for comparison of groups. For Table 1, an unpaired t-test was performed. Note that regression analysis is presented as r² values.

RESULTS

A model for generating HFIS. We tested whether we could predict resonance chamber length from the harmonic intervals calculated from our sound recording and analysis system. We generated sounds with an air jet that was moved in and out of a hollow cylindrical pipe. The vacuum pressure (~4 cmH₂O) generating the air jet was adjusted so that the air jet alone (in ambient air and not in a pipe) produced a sound intensity less
Table 1. Characteristics of children who made HFIS compared with the characteristics of children who did not make HFIS

<table>
<thead>
<tr>
<th>Sound Pattern</th>
<th>No HFIS</th>
<th>HFIS</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of subjects</td>
<td>12</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Sex, %male</td>
<td>67</td>
<td>59</td>
<td>0.68</td>
</tr>
<tr>
<td>Age, yr</td>
<td>9.2 ± 0.4</td>
<td>8.7 ± 0.5</td>
<td>0.52</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>40.0 ± 3.4</td>
<td>41.5 ± 4.1</td>
<td>0.81</td>
</tr>
<tr>
<td>Height, cm</td>
<td>138 ± 2.2</td>
<td>135 ± 2.9</td>
<td>0.35</td>
</tr>
<tr>
<td>BMI, z score</td>
<td>1.08 ± 0.42</td>
<td>1.38 ± 0.25</td>
<td>0.53</td>
</tr>
<tr>
<td>Arousal/h</td>
<td>5.0 ± 0.7</td>
<td>6.6 ± 1.0</td>
<td>0.26</td>
</tr>
<tr>
<td>OAHant</td>
<td>1.0 ± 0.3</td>
<td>7.6 ± 2.5</td>
<td>0.06</td>
</tr>
<tr>
<td>CAHII</td>
<td>1.5 ± 0.4</td>
<td>0.6 ± 0.2</td>
<td>0.047*</td>
</tr>
<tr>
<td>SnoreQ</td>
<td>2.4 ± 0.4</td>
<td>4.4 ± 0.2</td>
<td>0.001*</td>
</tr>
<tr>
<td>HFIS/h sleep</td>
<td>0 ± 0</td>
<td>223 ± 58</td>
<td>0.004*</td>
</tr>
<tr>
<td>HFIS intensity</td>
<td>0 ± 0</td>
<td>2.5 ± 0.3</td>
<td>0.001*</td>
</tr>
<tr>
<td>MRI narrowest, mm²</td>
<td>70.9 ± 22.5</td>
<td>20.5 ± 4.4</td>
<td>0.02*</td>
</tr>
<tr>
<td>MRI lips to soft palate, cm</td>
<td>9.2 ± 0.2</td>
<td>8.5 ± 0.3</td>
<td>0.11</td>
</tr>
<tr>
<td>MRI lips to larynx, cm</td>
<td>12.9 ± 0.3</td>
<td>12.8 ± 0.4</td>
<td>0.83</td>
</tr>
<tr>
<td>Closed harmonic pipe length, cm</td>
<td>10.2 ± 0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open harmonic pipe length, cm</td>
<td>13.9 ± 1.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SE for 29 subjects. BMI, body mass index; OAHant, obstructive apnea-hypopnea index; CAHII, central apnea-index; HFIS, high-frequency inspiratory sounds; MRI, magnetic resonance imaging. The scale of HFIS intensity is 0–5 and is defined in METHODS. Statistical comparison was by unpaired t-test. *Significant.

Fig. 1. Determinants of harmonic frequency and amplitude. A: pipe length determines harmonic frequency in open-ended pipes. The air jet produced a series of even harmonics when placed in pipes that were open on both ends. Pipe lengths were 32, 16, 12, 8, 6, and 4 cm. The data suggest that the open pipe amplified certain harmonic frequencies made by the air jet and that pipe length was the primary determinant of the harmonic frequency. Sound intensity is represented (low to high) as the colors black, dark blue, light blue, yellow, red, and white. B: pipe length determines harmonic frequency in closed-ended pipes. The air jet produced a series of odd harmonics when placed in pipes that were closed on one end. Pipe lengths were as in A. The data suggest that the closed-end pipe also amplified certain harmonic frequencies. C: air jet magnitude determines harmonic amplitude in an open-ended pipe. The air jet (at −4, −8, −12, and −16 cmH₂O of vacuum pressure) induced a fixed set of harmonics when inserted into an 8-cm-long pipe with both ends open. There was increased sound amplitude at higher pressures without alteration in harmonic frequency. D: air jet magnitude determines harmonic amplitude in a human mouth. The air jet was placed in 1 of the author’s mouth and produced a complex harmonic pattern that was “odd” in character, predicting a closed-pipe pattern. As air jet pressure was increased, so was harmonic frequency. The data suggest that flow (estimated from driving pressure) was the primary determinant of the sound amplitude.
These data suggest that the length of the rigid pipe was the primary source of the harmonic frequency.

We next evaluated the effect of increasing the air jet velocity by increasing the suction pressure. In an 8-cm-long open pipe, increasing the suction pressure from $-4$ to $-16$ cmH$_2$O increased the amplitude of the harmonics without altering the harmonic frequency intervals (some harmonics, not visible at lower pressures, were apparent at increased suction pressure; Fig. 1C). Similar results were observed when the air jet was placed in one of the author’s oral cavity: increasing suction pressure increased the amplitude of the harmonics without altering the harmonic frequency intervals (Fig. 1D).

These data suggested that 1) the length of the resonance chamber (the pipe) was the primary source of the harmonic frequency intervals and that 2) the loudness (amplitude) of the harmonics depended on the characteristics of air jet; i.e., more negative suction pressure (higher flow) induced louder harmonics (higher harmonic amplitudes).

**Patient studies on airway diameter.** We compared 17 children who made HFIS with 12 children who did not make HFIS (Table 1). Children who made HFIS had significantly higher scores on the parental snoring questionnaire (SnoreQ) and lower central apnea-hypopnea index than children who did not make HFIS. There were no statistical differences in age, sex, height, weight, or body mass index $z$ scores (9) between these two groups.

Our hypothesis states that children who make HFIS must create a high-velocity jet of air to induce harmonic resonance in the upper airway of sleeping children. This hypothesis requires a structural reason, such as inhalation through a narrowed upper airway, to generate the high-velocity jet of air. MRI scans of the upper airway were obtained, and the minimum upper airway cross-sectional area was calculated. In the 17 children who made HFIS, the narrowest airway area was at the level of the adenoids in 16 children and the tonsils in 1 child. In the 12 children who did not make HFIS, the narrowest airway area was at the level of the adenoids in 9 children, the tonsils and adenoids in 1 child, the tonsils in 1 child, and the soft palate in 1 child.

Children who made HFIS had significantly smaller narrowest airway area ($20.5 \pm 4.4$ mm$^2$ (means $\pm$ SE)) compared with children who did not make HFIS ($70.9 \pm 22.5$ mm$^2$; Table 1). Figure 2 shows MRIs from two children: the top panels show a normal airway (arrows) and the bottom panels show an airway with reduced cross-sectional area from enlarged adenoids (labeled A). Figure 3 shows the dependence of the number of HFIS generated per hour of sleep as a function of the MRI-measured narrowest airway area. HFIS were only observed when the MRI measured narrowest area was small (Fig. 3, top). There was a highly significant inverse relation between HFIS per hour and log$_{10}$ of the MRI narrowest area (Fig. 3, bottom; $r^2 = 0.55, P < 0.00001$).

**Patient studies on airway dimensions and airway resonance.** The above data suggest that children who generate HFIS have a narrowed airway. For our second test of the hypothesis, we need to show that the length of the upper airway, calculated from HFIS harmonic intervals, is similar to the length of the airway calculated from MRI scans. The airway long-dimension lengths (e.g., lips to the larynx) measured from MRIs of

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**Fig. 2.** Magnetic resonance images from a child with a normal large airway (top) and a narrowed airway (bottom). Left: sagittal magnetic resonance images. Right: axial cross-sectional magnetic resonance images of the airway. The horizontal line with a plus sign at one end on the left images is a calibration line 10 cm long. Arrows in top panels, narrowest area. “A” in bottom panels, adenoids. The child shown in top panels had a narrowest area of 85 mm$^2$ and did not make any high-frequency inspiratory sounds (HFIS). The child shown in the bottom panels had a narrowest area of 0 mm$^2$ and made 749 HFIS/h.
children who made HFIS did not differ from the measured values in children who did not make HFIS (Table 1).

In a blinded analysis, we evaluated the harmonics intervals in the HFIS. From these harmonic intervals, we calculated resonance chamber lengths. Figure 4 shows the FFTs calculated from recordings of four representative sleeping children with identifiable harmonic intervals. Each recording shows a series of harmonics with varying intensities. For each recording, there was a predominant harmonic pattern that is marked with a black bar at the right of each FFT. The predominant harmonic pattern of the top two recordings appears to be an open-pipe pattern (i.e., even harmonic intervals) with an estimated “pipe” length of 11.4 and 7.6 cm for the left and right recordings, respectively. The predominant harmonic pattern of the bottom two recordings appeared to be a closed-pipe pattern (i.e., odd harmonic intervals) with an estimated pipe length of 7.8 and 7.1 cm for the left and right recordings, respectively. Note that some harmonics were missing and some harmonics were louder, suggesting that sound was generated in a more complex resonator than a simple cylindrical pipe. Also, some recordings have other harmonics outside the integral pattern, e.g., the right lower recording also has some more complex harmonics at higher frequencies. Such additional harmonics are not unexpected given that there may be more than one resonating chamber, such as the mouth and the nasal cavity that could also resonate sound in these sleeping children.

Of the 17 children who made harmonic HFIS, 8 children made even harmonic HFIS characteristic of an “open-ended” resonance chamber. Their predicted chamber length was $13.9 \pm 1.3$ cm, a value similar to the length of their upper airway between their lips and the larynx measured from MRI scans of $13.4 \pm 0.4$ cm. Nine children made odd harmonic HFIS characteristic of a “closed-ended” resonance chamber. Their predicted chamber length was $10.2 \pm 0.9$ cm, a value similar to the length of their upper airway between their lips and the soft palate measured from MRI scans of $8.3 \pm 0.4$ cm. These data suggest that the upper airway could be the resonant chamber responsible for amplifying sounds at specific frequencies, specifically those frequencies characteristic of HFIS.

**DISCUSSION**

We find that sleeping children who generate HFIS have significantly narrower upper airways compared with children who do not make HFIS (Table 1, Fig. 3). We also find that the harmonics characteristics of HFIS predict that HFIS are generated by sound resonating in chambers whose lengths approximate the length of their upper airway (Table 1, Fig. 4). These results support the hypothesis that HFIS are generated when a high-velocity jet of air, produced by a narrowed airway, induces the upper airway to act as a resonating chamber generating sound with defined harmonics. In the future, we plan to test the third prediction of the hypothesis: whether children who make HFIS generate a high-velocity “air jet.”

We postulate that children with the narrowest airways must generate substantial subatmospheric intrapleural pressures to inhale. Such high pressures across a narrowed airway would produce high-velocity airflow. This high-velocity airflow would excite air in the distal upper airway and induce resonances in it that we describe as HFIS. We find that the amplitude of harmonics generated from an air jet primarily depended on pressure (Fig. 1, C and D). Hence, it is reasonable that there should be a negative correlation between narrowest upper airway cross-sectional area and the number of HFIS per hour as we found in Fig. 3.

Our data are partly compromised because the MRIs were performed while the children were awake rather than during sleep when HFIS are generated. Several recent studies showed that awake children with OSDB have smaller airways at the level of the tonsils and adenoids than children without OSDB (1, 5), a finding similar to our result. Similar studies found that the upper airway in adults with OSDB was smaller than the upper airway of adults without OSDB (7, 14). The upper airway is reported to decrease in size when adults fall asleep; this reduction in airway size was greater in adults with OSDB than in adults without OSDB (8). These studies suggest that the smaller airways we found in children who make HFIS (Fig. 3) are 1) likely to decrease in size when these children are asleep and 2) likely to be smaller than the airway size of sleeping children who do not make HFIS. Both of these will need to be tested by measuring airway size in sleeping children.

We found that the narrowest airway was at the level of the adenoids in most children who made HFIS. This is similar to
the study of Arens et al. (1), who found the smallest region was at the level of the adenoids where they overlapped with the superior portion of the tonsils. Our findings differed from those of Fregosi et al. (5), who found the narrowest area was at the level of the tonsils. Differences in technique may explain these differences: Fregosi et al. measured cross-sectional airway area in a series of axial parallel planes (see Fig. 1 in Ref. 5). In contrast, we measured airway cross-sectional area in a series of planes that were tilted to be perpendicular to the posterior wall of the airway (i.e., axial in the posterior pharynx but tilted between axial and coronal to image the superior sections of the airway). Our measurements correct for the curve in the airway from the posterior pharynx to the nasal cavity.

We found a striking similarity between resonance chamber length predicted by harmonic intervals and upper airway lengths measured from MRI scans. This suggests the upper airway is likely the resonance chamber producing HFIS. A closer look at the data seemed to suggest that upper airway length from the lips to the larynx approximated resonant chamber length in children who made HFIS with even harmonic intervals, i.e., an open-pipe pattern. The data also seems to suggest that upper airway length from the lips to the soft palate approximated the resonant chamber length observed in children who made HFIS with odd harmonics, i.e., a closed-pipe pattern. However, our data were not precise enough to clearly make this conclusion. We cannot distinguish whether the chamber generating HFIS was the oral cavity, the pharynx, the nasal chambers, the base of the tongue, or some combination of these. We have not yet been able to determine whether a closed vs. open resonance pattern has a correlation with location of obstruction on the awake MRI scans or with the degree of sleep apnea. Clearly, further work is required to determine what portion of the upper airway is the resonating chamber that generates HFIS.

In this study, the adenoids were the site for maximal airway narrowing in the 25 of the 29 children we studied (Fig. 2). This suggests the location of the high-velocity airflow could be the nasal airway at the level of the adenoids. When the nose is completely occluded by hypertrophied adenoids, however, and the child is breathing through their mouth, the location is more likely in the pharyngeal airway. We suspect in this circumstance it is where the tongue falls back against the soft palate, but it could occur anywhere in the pharyngeal airway, including the tongue base or the vocal cords. When the nasal airway is only partially occluded, children may breathe through both their nose and mouth, and there could be resonant sounds generated in both the nasal and pharyngeal airways. This could produce several different harmonic series.

Our results suggest that HFIS are generated in children with narrow airways when air in the distal upper airway is excited and the distal upper airway acts as a resonating chamber. We speculate that air moving rapidly through the narrow airway induces an air jet that excites the upper airway to act as a resonating chamber and produce HFIS. On the basis of the
physics of sound and on our studies with open and closed pipes, the frequencies of HFIS appear to depend on upper airway length and the amplitude of HFISs appears to depend on the velocity of the air jet. We therefore hypothesize that HFIS could be an index of the ventilatory effort required by children who have a narrowed upper airway. Further work is required to determine whether HFIS is an index of ventilatory effort and therefore of the severity of OSDB.

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