Evaluation of the human airway using cone-beam computerized tomography
Hung Hsiag Tso, BS,a Janice S. Lee, DDS, MD, MS,b John C. Huang, DMD, DMedSc,c Koutaro Maki, DDS, PhD,d David Hatcher, DDS, MSc, MRCD(C),e and Arthur J. Miller, PhD,f
San Francisco and Sacramento, California; and Tokyo, Japan
UNIVERSITY OF CALIFORNIA, DIAGNOSTIC DIGITAL IMAGING, AND SHOWA UNIVERSITY

Objective. The goal of this project was to define and measure human airway space with radiographic volumetric 3-dimensional imaging and digital reconstruction of the pharynx using cone-beam computerized tomography.
Study design. This was a randomized retrospective study. Ten patient scans were selected randomly from a pool of 196 subjects seeking dental treatment at the University of California, San Francisco. Digital Imaging and Communications in Medicine–format volume images were captured using a low-radiation rapid-scanning cone-beam computerized tomography system (Hitachi MercuRay).
Results. Detailed progressive rostrocaudal cross-sectional area histograms indicated that 8 of the 10 subjects demonstrated a region of maximum constriction near the oropharynx level. The most restricted cross-sectional area varied from 90 mm² to 360 mm².

Evaluation of the airway has become an important diagnostic test in several subspecialties of dentistry. Multiple orthodontic researchers have developed techniques to use full-head x-rays to determine airway obstruction, and the potential impact of high-resistance airways leading to abnormally developed increases in the vertical facial dimensions in young patients.1-6 Functional appliances have been developed by dentists to assist patients who suffer from sleep apnea after detailed magnetic resonance imaging (MRI) and computerized tomography (CT) studies of the entire airway.7-23 Oral surgeons provide mandibular and maxillary advancement to assist patients with sleep apnea problems, often using spiral CT analysis.24,25 The medical field has developed several approaches to evaluate the functioning airway during each breath, providing some excellent evaluations by noninvasive cine-MRI, CT, and endoscopic analysis, including using optical coherence tomography (OCT).26-35 Although these methods provide excellent evaluation of the airway, the advent of cone-beam computerized tomography (CBCT) has opened the opportunity to evaluate the cross-sectional area of the airway as well as the volumetric 3-dimensional (3D) depiction of the entire airway using a lower-radiation method than medical CT with a rapid (<20 seconds) scan that is noninvasive.36-40 We provide in the present study a concept on how to use CBCT to analyze the airway, indicating that the most restricted site should be determined by using the cross-sectional area, that the extent of the restriction should be noted in the airway, and that this should be compared with the volumetric rendering that gives an overview of the same factors.
Table I. Subjects by age and gender with linear, areal, and volumetric measurements of the airway.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Gender</th>
<th>Age (yrs)</th>
<th>Anteroposterior length (mm)</th>
<th>Most restricted cross-sectional area (mm²)</th>
<th>Most restricted volume (mm³)</th>
<th>Total volume (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>25</td>
<td>3</td>
<td>77</td>
<td>19,154</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>28</td>
<td>7</td>
<td>132</td>
<td>15,019</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>7</td>
<td>2,155</td>
<td>19,688</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>33</td>
<td>6.8</td>
<td>144</td>
<td>25,714</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>34</td>
<td>6.8</td>
<td>169</td>
<td>19,688</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>6.8</td>
<td>186</td>
<td>18,629</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>F</td>
<td>10.2</td>
<td>231</td>
<td>32,143</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>F</td>
<td>14</td>
<td>237</td>
<td>22,156</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>61</td>
<td>9</td>
<td>295</td>
<td>30,910</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>M</td>
<td>13.2</td>
<td>343</td>
<td>41,557</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

METHODS

Subjects

A retrospective analysis was conducted by randomly selecting 10 adult patients with Digital Imaging and Communication in Medicine (DICOM) datasets from a pool of 196 patients who were seeking treatment in the School of Dentistry, University of California, San Francisco (UCSF). The Institutional Review Board approved the project, and informed consent was obtained from each of the subjects before the CBCT scan. Patients were included if they had a normal class I occlusion and excluded if they demonstrated craniofacial anomalies or if the clinical record indicated a history of sleep apnea and other potential airway abnormalities. Five adult female and five adult male subjects were studied (Table I).

CBCT system

With most CBCT systems, a conical beam of x-rays that is sized to encompass a region of interest rotates around the patient’s head in a circular path. The CBCT system acquires image data usually in a single revolution of a paired source and set of detector arrays and collects a volume of information, as opposed to a stack of multiple slices of the scanned object as in conventional CT machines.

All CBCT scans were taken by the UCSF Division of Orthodontics 3D Craniofacial Function and Imaging Center using the Hitachi CB MercuRay device (Hitachi Medico Technology, Tokyo, Japan). The radiologic parameters used were 120 kV and 10 mA. With the patient sitting upright, a rotating source/detector gantry captured a volumetric image of the patient’s head, a process similar in nature to panoramic radiography. A 10-second scan acquired 288 primary images using a scalable 12” CCD detector that could be set in several field-of-view (FOV) modes. These primary images underwent a secondary reconstruction and were stored as 512 DICOM data files. The scanner used 12 bits/voxel (2^{12} = 4,096 shades of gray) and ranged from 0.200 mm³ to 0.376 mm³ for the theoretic voxel resolution mode, depending on the FOV. In this study, the facial mode with the 19-cm FOV was used and the spatial resolution of each voxel was 0.6 mm. The resulting data consisted of a cubic array of \(\sim 134,000,000 (512 \times 512 \times 512)\) isotropic voxels. Axial slice distance for each scan was 0.370 mm³.

The CBCT data from each subject was analyzed using the CBWorks software (CBWorks 2.0; CyberMed, Seoul, Korea). Raw data in the form of line integrals were used along with slice thickness by image reconstruction methods to yield cross-sectional images with voxel values that corresponded to the computed linear attenuation coefficients. There are \(2^n\) CT units for \(n\)-bit CT data, so for 12-bit data, there are 4,096 CT values assigned on a scale from −1,024 to +3,071 CT units. The scale is calibrated such that −1,024 CT unit is the attenuation produced by air, and 0 CT unit is the attenuation produced by water.

The patient’s orientation was corrected initially before doing the analysis using the Z function of the CBWorks software. While evaluating the patient in all 3 planes, the head was repositioned so that it was straight with no cant. The alignment of the lower border of the left and right orbital ridges was evaluated from the coronal view, the hard palate was aligned with the horizontal plane from the midsagittal view, and the alignment of the left and right zygomatic arches was noted in the horizontal image.

Evaluation of the airway using CBCT images

Using the CBWorks software, each patient was initially evaluated using the horizontal, sagittal, and coronal images (Fig. 1). The airway was digitally excised by defining a threshold range of CT units that occupied the airway which were values below the ranges for soft tissue and bone. Measurements could be performed on the cross-sectional area of each slice from the axial view, and the linear measures of the dorsoventral width of the airway were used to define the maximum constriction from the midline sagittal view. The software was then used to define the volume of the entire airway by first “segmenting” the regional space of interest.

Segmentation

Threshold segmentation was used to select the CT units within the airway. Because the air space exhibits a significantly greater negative CT unit than the more dense surrounding soft tissue, the sharp distinct high-contrast border produces a clean segmentation of the airway. By modifying the threshold limits, the appropriate range defined the tissue of interest within the...
volume of interest for a particular scan. Using this concept, a threshold isolation of CT units was selected to capture all empty spaces in the head and neck region, which also included other cavities, such as the maxillary sinuses and trabecular matrix within dense bones. Using the Region Of Interest editing tool function and the Volume of Interest editing tool, most undesired hollow structures were eliminated. The object was threshold segmented and slice edited by hand to remove any visible extraneous scatter, artifacts, or background, similar to the method described by Meehan et al.\(^4\) After segmentation, the resulting set of masks (highlighted areas representing each structure of interest within each slice of the CBCT scan) was rendered into a shaded surface mesh in the CBWork’s SSD tool. Parameters were set at high quality and unconstrained smoothing at a critical angle of 120°. This meant no loss or simplification of voxel position, and any sharp surface feature from the surface was considered to be a “step artifact” related to slice thickness and volume-averaging effects that could be removed from the surface data.

**Linear measurement**

The anterior-posterior (AP) dimension of the airway in the midline of the sagittal plane at the level of hard palate, just rostral to the hard palate, and at the most constricted site of the pharynx, just rostral to the upper esophageal sphincter, were measured with linear measurement tools at the midline of the sagittal view. The centermost sagittal position was located using the center of the anterior nasal spine as the landmark.

**Volume and cross-sectional area measurement**

Volume of the segmented region was displayed and recorded. The cross-sectional area of each axial slice was also displayed within the axial view quadrant and recorded. The inferior cut-off of the scan was designated as the first slice, and the slice numbers increased as they progressed superiority. Because the thickness of each slide was known to be 0.377 mm, it was possible to calculate the relative position of each axial slice in relation to the inferior border of the scan. The relative position of each axial slice showed the length in mm from the inferior cut-off reference slice. Using Microsoft Excel (Microsoft, Redmond, WA), the slice with the narrowest cross-sectional area was determined, establishing the most constricted site of the airway.

**Statistics**

The linear distance between the ventral and dorsal walls of the pharynx was determined at 3 levels. The cross-sectional area and shape of each slice at these 3 sites were then determined (Fig. 2), and compared on a histogram-like display of the change in cross-sectional area for each
slice beginning rostrally from the hard palate proceeding caudally to just above the vocal cords and upper esophageal sphincter. The segmented-rendered airway volume was then evaluated from both the frontal and lateral views (Fig. 3). The linear, areal, and volumetric measures were compared by linear regression analysis using a correlation coefficient (r) as well as with Spearman correlation.

RESULTS
Evaluation of the rostrocaudal change in cross-sectional area for all 10 patients sitting upright indicated that the area of maximum areal restriction varied but was more often in the oropharyngeal region (Fig. 4). One subject actually demonstrated a rostrocaudal range of restriction from the oropharynx to the rostral hypopharynx. Two subjects demonstrated their smallest cross-sectional area in the lower oropharynx or upper hypopharynx. In these 10 subjects, the smallest cross-sectional area for these patients sitting upright was 90-360 mm$^2$ (Table I).

Evaluation of the airway volume in the frontal view indicated much variation in shape with some asymmetries. This view also showed where restrictions would occur laterally. Reviewing the sagittal view of the airway volume showed that the widest dorsoventral region was at the rostral level of the hard palate and that at the level of oropharynx the more anterior or protruded position of the tongue would create an additional ventrally located space, which would include the valleculae. If the posterior tongue was separated from the soft palate, then it would create this ventrally located space of the pharynx. The epiglottis made an indentation into the space below the tongue. Defining the maximum restriction from this lateral volumetric view almost always indicated the region dorsal to the posterior tongue.

Comparing the maximum restricted site, as defined linearly from a midsagittal lateral view of the head, with the histogram display of the rostrocaudal cross-sectional area changes showed a high correlation coef-
ficient \( r = 0.87; \) Spearman rho = 0.73; Fig. 5, A, and Table 1). A shorter linear distance in the lateral view of the airway in the sagittal midline correlated with a smaller cross-sectional area, which was defined as the smallest cross-sectional area through the whole length of the pharynx. The airway with the smallest cross-sectional area had the smallest total volume of the airway \( r = 0.83; \) Spearman rho = 0.76; Fig. 5, B). There was a high correlation between the most constricted cross-sectional area of the airway and the total airway volume \( r = 0.83).\)

**DISCUSSION**

The present CBCT study of the airway demonstrates a feasible and reliable technique to obtain a quantitative assessment of the airway in a live human subject sitting upright or lying down, depending on the unit, with a low-radiation fast-scanning system (<60 seconds) that is much more financially viable than many current scanning systems (i.e., spiral CT, MRI).\(^{41,45,46}\) The system is highly accurate in its measurements, and the images are not distorted. The CT units do not correspond to the traditional medical CT numbers, but the relative range for different types of tissues provides a method to rapidly segment the airway. The latest software advancements can also simulate an endoscopic evaluation based on the relatively real-life volumetric recreations of the pharynx which we used in this study as surface volume renderings.

Earlier studies have focused on evaluating the airway to determine when its morphologic characteristics might relate to functional disorders, such as with restricted airways that induce mouth breathing or obstructive sleep apnea (OSA). Although some techniques can determine how the airway changes with each breath and demonstrate when it collapses,\(^{29}\) the advent of a more commonly used imaging system with CBCT provides a potential screening of the airway. Studies with positive pressure opening the airway do effectively treat obstruction, such as in OSA, and support the concept that a minimal airway is needed as well as prevention of collapse.\(^{47,48}\) The major weakness of using CBCT, however, is determining whether a static evaluation of the airway will provide a threshold of size or shape predictive of potential clinical problems. An extensive prospective study is warranted in which a broad spectrum of subjects needs to be evaluated from what is clinically defined as the normal population.

The present pilot study provides 3 methods to evaluate the airway and raises 4 important points:

1. When is a physiologically restricted airway evident in a CBCT image as defined by cross-sectional area, volume, and shape?
Fig. 4. Graphic representation of the change in the cross-sectional area of the airway for each of the 10 subjects proceeding caudally from the level of the nasopharynx to the hypopharynx. The most restricted site for the cross-sectional area varies among subjects, with 2 subjects restricted more caudally and 2 subjects demonstrating a rostrocaudal zone of restriction.
2. How would this airway adapt in these 3 measures in subjects with obstructive sleep apnea?

3. What are the airway dimensions in obligatory mouth breathers who develop an abnormally long vertical facial dimension?

4. How effective could this method be for studying patients after radiotherapy and/or partial removal of the tongue?

Studies in the field of imaging the airway have been extensive and emphasize that the airway dimensions can change with the phase of respiration. Studies using cine-MR images have shown how the airway changes behind the tongue. Recent work with a cine-CT system using a single-detector-row scanner shows how the airway changes at different rostrocaudal levels for 10-second scans. Although this study showed how an oral appliance, advancing the mandible, altered the airway shape and size, it emphasized that changes in the airway could occur more laterally than anteroposteriorly with enhanced cross-sectional area. This study also showed how 5 different levels of the airway would change during apnea. One of the weaknesses of our study is that the subject breathes normally in a 10-second scan, which would suggest that both inspiration and expiration would contribute to the airway volume. This issue needs to be addressed but must also not introduce an artificial mechanism for a subject to breathe such that the exercise evaluates a maneuver of the airway space instead of an airway during quiet breathing. It is also important that the subject does not swallow, cough, speak, or do any motor response other than breathing quietly, because these activities can alter the position of the tongue.

The Hitachi MercuRay scans the patient in an upright sitting position, which means, unlike the NewTom system and most medical CT scanners and MRI units, the subject is not imaged in the supine position. Cone-beam CT does have some inherent problems that can affect the image, including scattering, cupping with flat panel detectors, high signal-to-noise ratio with an x-ray image intensifier and CCD camera versus the flat panel detector, and difficulty viewing soft tissue such as muscle. One of the advantages of the Hitachi MercuRay is that it also has a stationary mode of a 10-second recording which can evaluate, in real time, movement of the oral and pharyngeal region, such as in respiration or swallowing. This stationary 10-second mode may prove to be extremely useful in evaluating how much the airway changes in a midsagittal view in an awake subject sitting upright.

Comparison of the most restricted cross-sectional area ranged from 90 to 360 mm² in the present study, an observation notably larger than those found in a spiral CT study in subjects with OSA whose average cross-sectional area was 67.1 mm². That earlier study of OSA subjects found a cross-sectional area of the airway slightly larger than a later study of OSA patients in which the most constricted cross-sectional mean area was 40 mm² and the control subjects had a mean value of 177.8 mm². That cross-sectional area decreased during maximum inspiration in the OSA patients to a mean value of 16.3 mm², and then to 15.0 mm² during maximum expiration. Such patients demonstrated complete obstruction during one of the phases of respiration. Evaluation of subjects with MRI during both waking and sleep indicated that the smallest cross-sectional area was located in the retropalatal area (i.e., behind the soft palate) in 13 of 15 subjects. Bhattacharyya et al.’s study, using helical CT scanning and reconstructions to render both volume and cross-sectional area, was unable to show a correlation between airway dimensions and sleep study parameters (i.e., blood oxygen saturation, number of apneic episodes, and their duration). Such findings suggested that airway function and potential obstruction do not correlate with the airway assessed in a quietly breathing individual. In
fact, some of the control subjects demonstrated complete obstruction of the airway during the neutral phase of respiration. However, other studies have indicated that OSA subjects do demonstrate smaller cross-sectional areas of the airway, suggesting that there is a range in size for the airway in normal subjects, and that subjects with OSA can be below this range.47–50

A detailed and extensive study of the variation of the airway in normal subjects and in subjects who fall into experimental groups, such as those with OSA or who develop long vertical facial dimensions, is needed. Extensive studies with conventional CT scanners have shown that subjects defined with a high apneic index also demonstrated certain anatomic characteristics, including a larger tongue, a retrognathic mandible, an anteroposterior discrepancy of the maxilla and mandible, a tendency toward an anterior open bite, and obesity.7 Techniques are now available to evaluate the airway shape and size using anatomic OCT, which emphasizes the concepts we see with CBCT, the changes in shape and area through the entire airway.29 This OCT technique can evaluate the subject in an awake or sleep state, supine or sitting up, and, most importantly, evaluate a given region of the pharyngeal airway over time, indicating changes in shape and size with the phases of respiration and during apneic spells as long as the subject is breathing slowly and the airway does not exceed a certain size. Such studies complement MRI studies of subjects which demonstrate that the retropalatal volume decreases by almost 20% while the retroglossal airway volume does not change significantly during both waking and sleep states.52 Our study supports the concept of including volumetric analysis, because it provides a new perspective on the airway and potential mechanisms of collapse and restriction.53 Particularly interesting is the concept that the lateral airway diameter reduces during sleep with thickening of the lateral pharyngeal walls as well as changes in the soft palate position and width, so that detailed analysis of the volume and shape will prove to be valuable. The field of evaluating the airway is improving and will continue to build on 3D analysis to complement other valuable approaches.53

CONCLUSION

The CBCT system provides a low-radiation rapid-scan capability to assess patients’ airway using highly correlative linear, cross-sectional area, and volumetric measurements that include assessing the morphometry of the airway. The most restricted region in a subject who is awake, sitting upright, and quietly breathing, varies as to its location in the pharynx but appears primarily in the oropharynx.

REFERENCES


