Automated 3-Dimensional Airway Analysis From Cone-Beam Computed Tomography Data

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The analysis and 3-dimensional (3D) imaging of the airway have become more common as technological developments in both imaging and computer analysis have advanced and converged during the past few years.1,2 These advances have been especially beneficial for the ability to understand and diagnose obstructed sleep disordered breathing (OSDB) and its relationship to the craniofacial anatomy. The improved availability of cone-beam computed tomography (CBCT), 3D imaging, and computer simulation in dentofacial analysis and treatment planning has facilitated the use of this method for evaluation of the airway.3-14 The currently available diagnosis and treatment planning methods for OSDB have limitations despite inclusion of the patient’s sleep history, nasendoscopy, polysomnography, and conventional imaging. A precise anatomic analysis of the airway that could be correlated with the severity of OSDB and be easily obtainable would be valuable for diagnosis and treatment planning. At present, the airway calculation from computed tomography data requires time-consuming manual data segmentation, the accuracy of which could be questionable. Automatic data segmentation has the ability to provide rapid and reliable airway analysis results.

The airway extending from the tip of the nose to the epiglottis can be visualized on the CBCT scan (Fig 1). Because the scan also includes the jaws, teeth, cranial base, spine, and facial soft tissues, there is an opportunity to evaluate the functional and developmental relationships among these structures. The skeletal support for the airway is provided by the cranial base (superiorly), spine (posteriorly), nasal septum (anterosuperiorly), jaws, and hyoid bone (anteriorly). The airway valves include the soft palate, tongue, and epiglottis. If airway obstructions or encroachments are present, visualization and calculation of the airway dimensions can identify and localize the source of the obstruction.

Evaluation of the airway using CT data is 3D and more precise than using traditional cephalometric radiographs but requires considerable manual manipulation of the data to achieve objective measurements.15 Medical CT has been used to study the airway changes by gender and age and after jaw surgery.5,16-18 A semi-assisted computer program was developed (3dMDVultus software, 3dMD, Atlanta, GA) to quickly and reliably calculate the measurements, area, and volume of the airway. The results are displayed virtually. The present study was designed to determine the accuracy and precision of the 3dMDVultus software using an airway phantom in different orientations as a test standard.

Materials and Methods

3dMDVultus is a software program (3dMD) that performs a semi-assisted metric analysis of the human airway image using CBCT. The airway is segmented out on the CBCT scan, and volumetric and linear measurements are calculated. The airway measurements include the linear anteroposterior and mediolateral distances, volumes, and cross-sectional areas acquired at specific spacing intervals. In the present study, the accuracy and precision of the 3dMDVultus software were evaluated using an airway phantom as a test standard. The phantom consisted of an air-filled plastic tube surrounded by water (Fig 2). Water was selected because it has an attenuation value equivalent to that of soft tissue. The circumference of the outer surface of the phantom and the inner airway were created to simulate the dimensions of a small human neck (31.93 and 7.976 cm, respectively). The phantom dimensions were measured to the nearest 0.01 mm using Fowler & NSK Max-Cal Electronic

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Digital Calipers (Fred V. Fowler Co, Newton, MA), and the volume of the phantom airway was calculated using the formula: \( \frac{\text{radius}^2 \times \pi \times \text{length}}{1000} \) cm\(^3\). The airway volume was confirmed using the water weight equivalent. The phantom airway was filled with water, and the weight of the water was determined using an Allied Fisher Scientific Scale (model 7224DA; Hanover Park, IL) and confirmed with a Sartorius Research Scale (model 160P; Data Weighing Systems, Inc, Elk Grove, MI). Both scales were calibrated using National Institute of Standards and Technology weights within the past month. The simulated phantom airway was imaged using 3 different orientations; parallel to the long (vertical) axis (Fig 2A) of the CBCT scan, horizontal to the long axis of the scan (Fig 2B), and at an angle (\(\sim 66^\circ\)) to the long (vertical) axis of the CBCT scan (Fig 2C). The phantom was imaged in the same CBCT scanner (iCAT; Imaging Sciences International, Hatfield, PA) using the following protocol: 13-cm field of view, 0.25-mm voxel size, and 40-s scan time. The scan data were imported into 3dMDVultus in a Digital Imaging and Communications in Medicine 3 multi-file format. The imported data were oriented to align the Cartesian coordinate system to match the long axis of the air column (Fig 3A). The airway was enhanced for automated segmentation (Fig 3B), and the region of interest was set for the measurement calculations (Fig 3C). The 3dMDVultus software automatically computes the airway volume, cross-sectional areas, and linear distances at all specified sites. The entire 3dMDVultus calculation sequence was repeated 10 times for each of the 3 scan orientations and compared with the test standard measurement.

**Results**

The phantom airway volume was computed by measurement to be 50.01 cm\(^3\) (radius 1.262 cm, length 10.06 cm). The airway volume calculated by the weight method was 50.2 and 50.12054 g on the 2 scales. The software consistently calculated the phantom volume as 49.0 ± 0.15 cm\(^3\). No significant differences were found between the airway measurements obtained using the 3dMDVultus semi-assisted software program generated from the CBCT data and those obtained using the manual calculation methods generated from the CT scans (\(P = .975\)).

The images acquired by CBCT were converted and stored digitally in computers. Sampling is the process of converting continuous analog signals such as anatomy to discrete digital data by recording data points of the analog signals at regular intervals in space. Quantization is the process of digitizing the amplitude.
of the continuous analog signals to a set of discrete values. For example, quantization of a black and white picture into a 12-bit digital image involves converting the value of each sampled point to an integer value from 0 to 4,096, with 0 representing black, 4,096 representing white, and the values in between representing the various shades and intensities of gray.

The ultimate goal of sampling is to take enough samples to enable an accurate reconstruction of the original image. The Nyquist sampling theorem defines
how often each sample should be taken in space for an accurate reconstruction of the original analog signals. Samples are taken in the unit of space (define as a pixel) in square millimeters for a 2-dimensional image or in a unit of space (define as a voxel) in cubic millimeters for a 3D image. The Nyquist sampling theorem states that for a continuous, band-limited analog signal to be recovered from a set of sample points, the samples should be taken at a rate greater than twice the greatest frequency of the original analog signal. For example, applying the Nyquist sampling theorem to digital image processing, to accurately visualize and represent anatomic structures that are at least 0.5 mm, a voxel size of 0.25 mm would be required.

When digitizing the amplitude of a continuous analog signal, the discrete value representing the voxel will be the average of all anatomic structures within the voxel. When the anatomic structures within the voxel are relatively homogenous (ie, the voxel contains all hard tissue, all soft tissue, or all air), the final average will be representative of the structures. However, when the voxel contains a mixture of soft tissue and air, especially when the original analog signal differs dramatically, the average value of the soft tissue and air will not be representative of either structure. When a number of voxels in proximity are misrepresented because of the effects of volume averaging, the ambiguous region could potentially result in misinterpretation and might not create a precise boundary condition for anatomic segmentation.

Discussion

The radiation dose from CBCT is significantly less than that for other computed tomographic imaging methods such as medical CT and is within the range of traditional dental imaging methods. The superior anatomic information available with less radiation using CBCT is establishing it as the preferred imaging modality in dentistry and medicine. Recently, awareness has increased among practitioners regarding the relationship among craniofacial structures, airway anatomy, and OSDB. The airway anatomy and evaluation for OSDB will be more accurate and informative when 3D imaging is used. Other applications of 3D imaging include the evaluation of changes in the airway resulting from surgery of the oral soft tissues and jaws.

The accuracy of predicting airway space changes from lateral cephalometric radiographs is ±1.5 mm. In a study by Muto et al, a set back of the mandible of 1 cm resulted in a 0.4-mm decrease in the airway in the anteroposterior dimension only. The usefulness of these cephalometric studies is limited, because the data are obtained in 2 dimensions. CT imaging is superior, both in accuracy and in the ability to measure in 3 dimensions. Airway space measurement has been shown to be quite accurate using CBCT scans. In addition, reconstructing the airway from CBCT data and segmentation techniques as we have used in the present has proved reliable. Kim et al studied the accuracy of a semiautomatic measurement of airway dimension using medical CT and the orientation of an artificial airway. They found that the obliquity of the slice could cause error and recommended that the images be reconstructed with a standard kernel and a 0.75-mm slice thickness for the best results. This is also something we found to require programming changes to eliminate error from obliquity. In addition, CBCT might have advantages in this regard compared with multidetector CT, because the voxels are isotrophic with CBCT scans but might not
be with MDCT. This can then influence the accuracy of the reconstructions that are off the scan plane.

Multivariate analysis showed both retroglossal space \( (P = .027) \) and retropalatal space \( (P = .0036) \) to be predictive of the respiratory disturbance index. Li et al\(^\text{11}\) have also demonstrated a relationship between the airway area and the likelihood of obstructive sleep apnea (OSA). The probability of severe OSA is high with an airway area less than 52 mm\(^2\), the probability is intermediate if the airway is 52 to 110 mm\(^2\), and is low if the airway is greater than 110 mm\(^2\).\(^\text{8,9,12}\) Lowe et al\(^\text{8}\) demonstrated that most of the constrictions occur in the oropharynx with a mean airway volume of 13.89 \( \pm \) 5.33 cm\(^3\). Barkdul et al\(^\text{5}\) demonstrated a correlation between the retrolingual cross-sectional airway and OSA when this area was less than 4% of the cross-sectional area of the cervicomandibular ring.

In the present study, we have shown that measurement of the 3D airway from CBCT data using a semiautomated software program is accurate, reliable, and fast. Imaging of the upper airway using CBCT is valuable to identify the exact location and nature of the obstruction in obstructive sleep apnea. Incorporation of this into daily practice will allow practitioners to readily evaluate and screen their patients for anatomically related OSDB (Fig 4). This is especially important in the adolescent population because many already seek orthodontic treatment for dentofacial deformities associated with OSDB.

**Report of a Case**

A 55-year-old woman presented to the clinic with a history of OSA and a polysomnogram with a respiratory disturbance index of 19.9, placing her at moderate risk of OSA. Clinically and radiographically she presented with bimaxillary retrusion. Subsequently, she underwent maxillary and mandibular advancement of 1 cm. An advancement genioplasty, including genioglossus advancement, was performed. The pre- and postoperative airway dimensions were analyzed using the 3dMD airway program we have described (Figs 3, 4). The smallest preoperative airway space was 6.62 mm\(^2\). This space had increased to 112.39 mm\(^2\) postoperatively (Figs 5, 6). An overlay of these changes and the volumetric changes are shown in Figure 7. The significance of using CBCT imaging and 3dMDVultus software is apparent by the precise location of the anatomic region of airway obstruction and the illustration of the change in airway space pre- and postoperatively in this patient.

**References**


