Three-dimensional analysis of the airway with cone-beam computed tomography

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Introduction: In this study, using a cone-beam computed tomography system, we evaluated the airways of 30 adults. Methods: The shapes of the 3-dimensional volume of the airway were analyzed and compared among the subjects by using surface superimposition software techniques. Results: The airway had the greatest variability in the hypopharynx, in the region below the epiglottis, and above the vocal folds. Moderate variation was apparent at the nares, behind the soft palate, and at the base of the tongue. Conservation of form was seen at the central portion of the nasal airway surrounding the inferior turbinate. Conclusions: The potential for comparing the shape of the airway among subjects is possible. (Am J Orthod Dentofacial Orthop 2011;140:607-15)

Many studies in orthodontics have focused on the airway and its potential importance to modifying the development of the craniofacial region. Much of this research has studied how the airway is implicated in developing abnormally long vertical facial dimensions.1-3 Orthodontists have also been actively involved in evaluating the airway and treating subjects with particular types of sleep apnea.4-6 With the advent of low-radiation, rapid computed tomography (CT) scanning,7-11 the potential for orthodontists to assess craniofacial growth in 3 dimensions is now available,12,13 and with that analysis is the capability of evaluating the complete airway.14,15

Determining the airway from images generated by cone-beam CT (CBCT) includes defining the most effective anatomic landmarks. Many previous studies have evaluated the airway by using 2-dimensional cephalometric analyses. Tourné16 showed that the bony nasopharynx extends from hormion (the most dorsal contact point of the vomer on the body of the sphenoid) to the level of the hard palate and foramen magnum. The pharynx’s structural volume increases by approximately 80% during growth.17 Transverse pharyngeal growth at the pterygoid hamulus is completed at 2 years of age.18 Choanal width increases about 23% by maturity with remodeling at the pterygoid laminae.17 The sagittal diameter of the nasopharynx, measured from the posterior nasal spine to basion, increases only 9% because of the influence of cranial base flexure (angle formed by sella to nasion to basion), since an acute angle leads to more vertical pharyngeal development.19 Hormion is displaced dorsally, increasing the length of the roof of the nasal cavity, but the posterior nasal spine has an even greater dorsal displacement.20,21 The vomer’s dorsal border and the clivus become upright, and the concurrent descent of the posterior nasal spine and basion with age tends to reduce the angle of the nasopharyngeal roof, but this might be cancelled with bone apposition at the pharyngeal aspect of the clivus. This growth counters the contribution of the growth of the spheno-occipital synchondrosis to nasopharyngeal depth, and probably contributes to most of the increase in pharyngeal depth. The vertebral body of the atlas might better represent the true posterior limit of the anteroposterior dimension of the pharynx, but the growth effects are similar. The contribution of apposition at the posterior palatine border is minimized relative to growth at the transpalatal suture and the tuberosities. This backward growth effect is compensated by secondary maxillary anterior displacement from cranial base growth. The main growth direction of the pharynx is vertical, with downward movement of the palate and primarily vertical growth at the spheno-occipital synchondrosis. Growth at these areas increases the height.
of the bony nasopharynx by 38% during childhood, and this dimension accounts for most of the increase in pharyngeal capacity, continuing until 13 years of age (female) or 18 years of age (male).

Adenoid vegetation is the most frequently cited cause of airway obstruction. The lymphoid tissue increases rapidly in size during infancy, slows thereafter, peaks before adolescence, and declines in the adult. Some evidence from cephalometric studies suggests that the adenoids increase during the preschool and primary grade years and then involute during preadolescence and adolescence. Lymphoid tissue does facilitate velopharyngeal closure but can result in blockage of the airway. The absolute size of the adenoids is not as important as the relative space that the mass occupies about 0.4 to 0.6 cm², shifting a significant amount of air orally and reducing airway resistance to a normal level. If morphologic changes are caused by airway impairment, other factors such as a large tongue, large tonsils, or a long, draping velum, could be significant contributing factors.

These studies can now be complemented by 3-dimensional (3D) evaluation of the airway in a subject seeking orthodontic treatment. Many techniques are effective in evaluating the airway volume and include magnetic resonance imaging, magnetic resonance imaging, spiral CT, and optical coherence tomography. In this article, we propose 1 method using CBCT to compare the 3D airway among subjects.

MATERIAL AND METHODS

CBCT data sets acquired from 30 patients were used in this study. Some scans of patients with pathologic conditions were included, with 4 being evaluated for temporomandibular disorders, 1 with a pneumocele of the right maxillary antrum, and 1 with an odontogenic cyst surrounding an impacted mandibular third molar. Scans of subjects with developmental conditions such as impacted teeth and orofacial clefts (1 subject) were permitted. Selection to homogenize the sample with respect to age, sex, and ethnicity was not specifically performed. The sample included 13 male and 17 female subjects with an average age of 22 years 8 months ± 12 years 1 month (median, 19 years 2 months). Most were white (17), followed by Asian (6), Hispanic (5), and African American (2). The most common reasons for referral for the CBCT scan were impacted teeth (10 subjects) and temporomandibular joint or temporomandibular disorder evaluation (8 subjects).

CBCT data was acquired from 2 systems: the NewTom QR DVT 9000 (Aperio, Sarasota, Fl) in a private radiology laboratory in Sacramento, California, and the CB MercuRay (Hitachi Medico Technology, Tokyo, Japan) at the Division of Orthodontics, University of California at San Francisco. The patient is supine in the NewTom and upright with the CB MercuRay; this could modify the shape of the airway. However, the primary purpose of this study was to demonstrate the variability in airway shape and the methods to compare these shapes.

The entire airway as a single unit was threshold segmented by using the CT numbers of each voxel and edited by hand with each transverse slice to remove any visible extraneous scatter, artifacts, or background, similar to the method described by Meehan et al. For areas with widely different thresholds, a combination of threshold segmentation and manual slice editing was used to obtain refined surfaces with minimal artifacts. The segmentation process involved using the sculpt tool of CBWorks (CBWorks 1.0; CyberMed Inc., Seoul, Korea) to narrow the scan into a volume of interest including only the structure that was to be segmented.
Threshold segmentation tools were used to isolate the osseous structures and the airway space from the data. Details in this approach have previously been published.\textsuperscript{42,43,45} After segmentation, the resulting set of masks (highlighted areas representing each structure of interest in each image slice of the CBCT scan) was rendered into a shaded surface mesh in the CBWorks' Shaded Surface Display tool. The 3D resulting surface meshes were exported from CBWorks in a Virtual Reality Modeling Language (.vrl) format into Amira software (version 3.1, Mercury Computer Systems, Berlin, Germany) for further analysis.

Due to limitations in the ability of the software to solve the problem of comparing nonhomeomorphic surfaces (surfaces that do not correspond in topology and cannot be transformed into one another by continuous and invertible mapping) or numbers of nodes (each voxel comprising the surface becomes a node in a tetrahedral mesh in which each voxel is connected to its 3 nearest neighbors), a reference structure was selected for indirect comparison of the individual surfaces. The reference surface consisted of 1 surface model of 1 patient, who was considered average as determined from a lateral view. The reference surface was nonrigidly transformed into each individual surface to provide a set of 30 surfaces of identical topology with the same number of nodes. The nonrigid transformation was completed by embedding 27 landmarks in each airway by using the Amira landmark tool (Table). Landmarks were embedded pairwise in the arbitrary reference and in each individual structure. The Amira landmark surface warp tool was set in a rigid transformation method to align the surfaces based on the embedded landmarks. Individual surfaces were then enlarged or compressed uniformly in the x-, y-, and z-dimensions by hand with the Amira transform editor dialog to scale each surface to the same size as the arbitrary reference surface.

Once the surfaces were aligned and scaled, a subset of 7 landmarks was used to identify the mathematically “most average” surface and to rank the remaining surfaces relative to it. Because the objects were now of similar alignment and size, the remaining differences in the surfaces were primarily related to differences in shape. To simplify the analytic calculations, these 7 landmarks, representing the basic form of each structure, were defined and used with all 30 forms including 4 shapes that did not extend fully rostrally and caudally. The x, y, and z coordinates of the 7 landmarks (Ad, left and right NasA, ConPS, ConPI, IAM-S, PA, and BT; Table) and the rectangular coordinate values were used.

By averaging the coordinate data for each data set, the centroid of each coordinate set was determined (Fig 1). Mean centroid coordinates were determined by averaging the coordinate values of the individual centroids. All data sets were centered at a common centroid located at the origin by subtracting the individual centroid coordinates from each landmark’s coordinates. The distance for each landmark of each set to its corresponding centroid was then calculated. The average distance of all landmark points in each set to the centroid was determined to be the centroid size of the data set. If scaling was correct, the data sets should be of identical centroid size. Manual scaling was generally within 3% to 5% of the calculated mean centroid size. Therefore, a correction factor (ratio of the mean centroid size to the individual centroid size) was applied to the

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Description</th>
<th>Bilateral point</th>
</tr>
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<tbody>
<tr>
<td>NarPM</td>
<td>Anteromedial vertex of the impression of the naris</td>
<td>Yes</td>
</tr>
<tr>
<td>NarAM</td>
<td>Posteromedial vertex of the impression of the naris</td>
<td>Yes</td>
</tr>
<tr>
<td>NarL</td>
<td>Lateral vertex of the impression of the naris</td>
<td>Yes</td>
</tr>
<tr>
<td>NasA</td>
<td>Most medioinferior point on the reflex of the anterior nasal airway</td>
<td>Yes</td>
</tr>
<tr>
<td>ConPS</td>
<td>Posterosuperior aspect of impression of inferior nasal concha</td>
<td>Yes</td>
</tr>
<tr>
<td>ConPI</td>
<td>Posteroinferior aspect of impression of inferior nasal concha</td>
<td>Yes</td>
</tr>
<tr>
<td>IAM-S</td>
<td>Most superior point on impression of internal auditory meatus</td>
<td>Yes</td>
</tr>
<tr>
<td>IAM-I</td>
<td>Most inferior point on impression of internal auditory meatus</td>
<td>Yes</td>
</tr>
<tr>
<td>FR-S</td>
<td>Most superior point on the base of the impression of Rosenmüller’s fossa</td>
<td>Yes</td>
</tr>
<tr>
<td>FR-I</td>
<td>Most inferior point on the base of the impression of Rosenmüller’s fossa</td>
<td>Yes</td>
</tr>
<tr>
<td>FR-D</td>
<td>Most dorsosuperior point at the height of the impression of Rosenmüller’s fossa</td>
<td>Yes</td>
</tr>
<tr>
<td>PW-C</td>
<td>Greatest convexity on the impression of the lateral aspect of the posterior pharyngeal wall</td>
<td>Yes</td>
</tr>
<tr>
<td>PA</td>
<td>Most lateroinferior point at the junction of the impressions of the soft palate and anterior pharyngeal wall</td>
<td>Yes</td>
</tr>
<tr>
<td>BT</td>
<td>Most lateroinferior aspect of the impression of the base of the tongue</td>
<td>Yes</td>
</tr>
<tr>
<td>EJ-L</td>
<td>Most lateroinferior point on the impression of the esophageal junction</td>
<td>Yes</td>
</tr>
<tr>
<td>EJ-C</td>
<td>Most inferior point at the central aspect of the impression of the esophageal junction</td>
<td>No</td>
</tr>
<tr>
<td>VF-L</td>
<td>Most posterolateral point on impression of vocal folds</td>
<td>Yes</td>
</tr>
<tr>
<td>VF-A</td>
<td>Most anteroventral point on impression of vocal folds</td>
<td>Yes</td>
</tr>
<tr>
<td>Ad</td>
<td>Most dorsolateral point on impression of adenoid tonsil</td>
<td>No</td>
</tr>
</tbody>
</table>
coordinate values of each data set to scale all sets perfectly to a common centroid size. These steps of aligning the individual coordinate systems about a common centroid and scaling them to a common centroid size constituted a Procrustes transformation of the coordinate data.

The root mean square error of each data set relative to the set of average landmark coordinates was determined. Root mean square error provides a way to determine how well the mean coordinate values fit each data set and provides part of the information necessary to rank the surfaces. Because root mean square error is always positively signed, arranging data sets from least to greatest root mean square errors orders each set in increasing distance from the mean but does not indicate whether each set is smaller or larger than the mean or average landmark coordinates (Fig 2). To give a sign to each root mean square rank, the average x, y, and z coordinates for each landmark were subtracted from each landmark coordinate. The signs of the difference for each component of each coordinate were recorded as more than 0 (assigned a value of 1) or less than 0 (assigned a value of -1). The sign of the sum of the landmark x, y, and z component differences was set to be the sign of the root mean square error. The signed root mean square errors were then ranked from 1 to 30 (Fig 3). The data set with the smallest root mean square error was the reference surface for the surface-warping procedure.

For the surface warping, models of each surface homeomorphic to the reference surface were created by nonrigid transformations of the reference surface. In this process, the same set of 27 landmarks was embedded in each airway as was used in the alignment to the arbitrary reference surface by using the Amira landmark tool. These settings were chosen because they yielded the visually best overall fidelity to the initial individual surface of the warped reference surface over other available combinations of the same settings and over a Bookstein transformation, which maintains the fidelity of the corresponding point pairs in the warping procedure but lacked the degree of overall fidelity observed in the flow.
transformation method. The reference surface, which was one of the 30 surfaces, was warped to the remaining 29 surfaces in groups of 5, primarily because of limitations of the computer hardware and software. Groups for warping were determined by the signed root mean square rank of the individual surfaces, so that surfaces 1 through 5, 6 through 10, 11 through 15, 16 through 20, 21 through 25, and 26 through 30 were clustered together. Each group of 5 surfaces was then combined by weighted surface interpolation to yield a local average surface. The 6 local average surfaces were then interpolated again to yield the overall average shape.

With the mean surfaces generated, the next step to make the 3D description of anatomic structures useful was to add a color map depicting the variability across each structure in the sample. First, to remove rotational and translational differences, the warped version of each surface was aligned to the coordinate system of the overall average surface by using the Amira tool, alignsurfaces, which minimized the root mean square distance between points of the model surface to the corresponding closest points on the reference surface by using the iterative closest point algorithm. Colors were set from 0 mm (dark blue) to 3 mm (bright red), and the included portion of the spectrum was divided proportionally. Color maps were generated for the warped reference surface version of each airway. An interpolation procedure similar to that performed to create the warped reference surface version of each airway was completed, yielding 6 local color maps applied to the local average surfaces. The 6 local average
surfaces and their color maps were subsequently put through another interpolation step to produce a surface representing the overall mean form with an associated color map describing variations of the surface in the sample population.

RESULTS

The airways ranked by signed root mean square errors are shown in lateral (Fig 4) and frontal (Fig 5) views. This spectrum roughly corresponds to thinking of the airways as small and more vertical at the minus root mean square end, and large and more horizontal at the plus root mean square end. Asymmetries of the airway were particularly noted in the frontal views. Extreme narrowing or restrictions were evident in both the lateral and frontal views of the airway. The distance color map for the airway was imposed on the mean surface along with an aligned and scaled translucent individual airway. For the airway, constriction of the overall tubular structure was judged at the nasal airway, nasopharynx, oropharynx, and hypopharynx. The airway components were evaluated as inside (constricted), similar to, or outside (dilated) the mean, and assigned respective values of −1, 0, or 1. The airway had the greatest variability in the hypopharynx, in the region below the epiglottis and surrounding the vocal folds (Figs 6 and 7). Moderate variation was apparent at the nares, behind the soft palate, and at the base of the tongue. Conservation was seen at the central portion of the nasal airway surrounding the inferior turbinate.

DISCUSSION

CBCT is suited to aiding our understanding the upper airway; all of the intricacies are visible and not hidden in the shadows of x-ray projections. In addition, surface data that can be derived from the CT studies can be manipulated in CT, engineering, and mathematical software. These types of programs not only improve visualization of head and neck anatomy, but also open orthodontics to the possibilities of integrating...
sophisticated morphometric methodologies with a physiologic understanding of the fluid dynamics of air passing through the nose and throat. The segmentation techniques used in this study allow incorporation of conventional linear and angular measurements into graphic, shape-based strategies that help to describe the features of a patient in the context of overall population variation.

Our data suggest that subjects can vary much more in the hypopharyngeal region than at the oropharynx or nasopharynx. However, part of this finding might also depend on the position of the centroid, which was defined predominantly in the central region of the airway and used for registration across subjects. It was expected that there would be fewer changes in shape close to the registration center and that greater changes would be evident farther from the registration site. The location of the landmarks and whether they represent peripheral boundaries of the airway and its general shape can affect the centroid. Although we did not evaluate the wide variety of problems and issues that can affect the airway, including subjects with chronic sleep apnea, this study does demonstrate that the airway has some variability in shape. We were particularly interested in

Fig 6. Six airway color maps, lateral view. Each airway represents a warping of the reference surface by using groups of 5 surfaces at a time and warping by the signed root mean square rank of the individual surfaces. Each of these 6 surfaces was combined to yield an overall average shape. The spectrum ranges from 0 mm (dark blue) to 3 mm (red).

Fig 7. Six airway color maps, frontal aspect. The spectrum ranges from 0 mm (dark blue) to 3 mm (red).
the limits of normal structures for the airway vs subjects who have an airway obstruction.\textsuperscript{39,46,47} We believe that CBCT will provide the tool for orthodontists to determine whether a patient, particularly a young patient, has severe enlargement of tissues that impinge on the airway, and CBCT will also provide a range of shapes and sizes that will function for normal airways.

The issue also arises as to what a CBCT 3D shape analyzes. CBCT systems differ in the time to scan a subject; the time will include several inspirations and expirations that can significantly modify the shape of the airway. In addition, the airway would modify its shape depending on whether the patient was lying supine or sitting upright. The final airway shape might represent a complex extrapolation of form over the period of scanning, and comparison of CBCT scans with other methods that accurately portray the change in airway during each comparison of CBCT scans with other methods that can significantly modify the shape of the airway. Additionally, the airway would modify its shape depending on the fact that regions of restriction are evident.

There is some parallel in applications between the 2-dimensional lateral headfilm used to evaluate the airway and the CBCT evaluation, in that the lateral full headfilm is taken quickly during 1 moment in time, but that shape and dimension of the airway can be potentially diagnostic for certain conditions that include restriction.\textsuperscript{39,46,47} In contrast, CBCT can evaluate the cross-sectional area, the volume, and the 3D form, and provides a more accurate review of the anatomy than a 2-dimensional lateral view, since it defines 1 key characteristic that modifies airflow, which relates to the radius of the cross-sectional area.\textsuperscript{4,15,41,54} We did not evaluate the airway cross-sectional area in this study but have emphasized the differences in 3D form and the fact that regions of restriction are evident.

CONCLUSIONS

CBCT provides a method to render a 3D volume of the airway through segmentation of voxels with similar CT numbers.

Defining landmarks of the airway provided a method to superimpose 3D rendered surfaces. Three-dimensional surfaces were aligned and scaled to the same size by using a reference surface considered to be an average airway and chosen arbitrarily. A small number of 7 landmarks were then used to define how each surface-rendered airway could be superimposed and compared quantitatively by using root mean square analysis to rank the images from the average or reference surface.

REFERENCES