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Accuracy and reliability of cone-beam computed tomography for airway volume analysis

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SUMMARY The purpose of the present study was to evaluate the accuracy and reliability of airway volume digital measurements of cone-beam computed tomography (CBCT) compared with the manual measurements of an airway model. An acrylic airway model was constructed and attached to a human dry skull in the natural position of the airway passage. The total and internal airway volumes, as well as the most constricted airway area, were measured manually on the model and on the CBCTs taken after the model was attached to the skull. The CBCT images were analysed using the Dolphin3D (Dolphin Imaging & Management solutions, Chatsworth, California, USA) software. Reliability and accuracy were assessed by using intraclass correlation and Student's *t*-test. A $P \leq 0.05$ was considered statistically significant. No significant statistical difference was found between the total, the internal airway volume, and the most constricted airway area measured on CBCTs compared with the manual measurements. The intra-examiner reliability was high for all measurements recorded from both methods ($r \geq 0.90$). These results suggested that the three-dimensional CBCT digital measurements of the airway volume and the most constricted area of the airway are reliable and accurate. The use of CBCT imaging for the assessment of the airway can provide clinically useful information in orthodontics.

Introduction

Airway volume and respiratory function are highly relevant to the orthodontic specialty. Studies have confirmed that airway problems are significantly related to different types of malocclusion and that nasal obstruction is a major aetiological factor for dentofacial anomalies (Linder-Aronson, 1979; Diamond, 1980; Kirjavainen and Kirjavainen, 2007). For example, in growing patients with skeletal discrepancies and signs of adenoid facies, early diagnosis, prediction, and assessment of the functional aetiological factors are critical for the restoration of normal craniofacial growth and the stability of the treatment outcome (Arun *et al.*, 2003; Kirjavainen, and Kirjavainen, 2007). Evaluation of the airway is an essential diagnostic step for patients with breathing disorders. Compared to normal subjects, obstructive sleep apnea (OSA) subjects have considerable craniofacial differences, such as the size and position of the mandible, enlargement of the posterior airway space, and size of the tongue and the soft palate (Ogawa *et al.*, 2007). In these patients, airway assessment has been mostly performed on two-dimensional lateral cephalograms by identifying special landmarks and measuring various lengths and areas in the airway region (Martin *et al.*, 2006).

Angle (1907) showed that Class II division 1 malocclusion is associated with obstruction of the upper pharyngeal airway and mouth breathing. de Freitas *et al.* (2006) concluded that the upper and lower pharyngeal airway width is not associated with Class I or Class II malocclusions. However, Kirjavainen and Kirjavainen (2007) reported that in Class II malocclusion, there is an association with a narrower upper airway structure even without retrognathia. Although Trenouth and Timms (1999) showed that the oropharyngeal airway was positively correlated with length of the mandible, none of the subjects with short mandibular length in their study had OSA.

Most of the airway studies relating airway anatomy and the craniofacial growth and development are limited because of using the two-dimensional lateral or frontal cephalograms which cannot identify the soft tissue contour in the third dimension thus limiting evaluation of areas and volumes. Currently, the advances in computed tomography (CT) imaging and the three-dimensional technology allow better visualization of the airway and volumetric analysis (Aboudara *et al.*, 2009). Clinicians can more easily perform the volumetric measurements and also calculate the cross-sectional areas of the airway in three planes of space: coronal, sagittal, and axial (Schwab, 1998). The axial plane, which is not visualized on a lateral cephalogram, is the most physiologically relevant plane because it is perpendicular to the airflow (Isono *et al.*, 1993; Abramson *et al.*, 2010). Cone-beam CT (CBCT) systems have been developed specifically for the maxillofacial region with the advantage of the reduced radiation doses compared with conventional CT. Accurate and easy evaluation of the airway anatomy has been possible using those CBCT systems (Mozzo *et al.*, 1998; Sukovic, 2003; El and Palomo, 2010). Although numerous studies have been published using CBCT to evaluate airway, few have addressed the accuracy of the measures. The aim of the present study was to evaluate the accuracy and reliability of the airway volume measured digitally on CBCTs as well as the most constricted area in the airway compared to the manual measurements made on an airway model.

Materials and methods

A wax model was carved in a shape matching the airway passage in anatomy and size to be used for measuring the airway volume manually. The model was then attached to a dry skull of a child in the position of the natural airway. During the initial wax carving, the area just below the epiglottis was carved narrower as to present the most constricted area in the airway. Using silicone impression material, an impression was taken for the wax model and then poured with plaster of Paris converting it to a stone model. The stone airway model was then adjusted on the platform of Biostar pressure molding machine (Great Lakes Orthodontics, Tonawanda, New York, USA) and coated with a transparent acrylic sheet. After the acrylic was hardened, the stone model was removed from inside and a transparent air-filled acrylic airway model was created (Figure 1).

The total airway volume was measured manually using the displacement method by immersing the model in a graduated measuring beaker (1 ml graduation interval) filled by water to a certain level and calculating the difference in water level before and after immersion. The internal airway volume was measured manually using 20–1000 µl pipette to calculate the amount of water used to fill the model.

The model was then positioned inside the skull in its natural position just below the pharyngeal tubercle. The upper anterior end was lightly glued to the posterior border of the vomer bone touching the basilar part of the occipital bone posteriorly and just behind the nasal cavity from the anterior side to simulate normal position of the airway with overlapping hard tissue structures (Figure 2).

The human skull with the installed airway model was scanned using the iCAT CBCT Unit (Imaging Sciences International, Hatfield, Pennsylvania, USA) using the following protocol: 13 cm field of view, 0.4 mm voxel size, and 8.9 seconds scan time. The scan data were imported using Dolphin3D imaging software (version 11.5; Dolphin Imaging & Management Solutions, Chatworth, California, USA). The same software was used then to measure and calculate the total and internal airway volume as well as the most constricted airway area. The total airway model was measured using the sculpting tool of the software. A cropping polygon was drawn around the boundaries of the model. Next, the cutting-out option was selected to remove the noises exterior to the polygon boundaries. The same steps were repeated from all the perspective views (sagittal, frontal, top, and bottom) until all the noises were removed and the model was cropped as one unit with a clear area around. The calculation was then done to the final sculpting model in cubic millimetre. The internal volume was measured after tracing the boundaries of the airway model where the software then filled and calculated the area in cubic millimetre. After identifying the upper and lower limits of the airway, the software detected the most constricted airway area automatically and calculated its surface area in square millimetre (Figur 3).

To measure the most constricted area of the airway manually, the model was horizontally cut at the same location planned during the carving step to present the most constricted area of the airway (just below the epiglottis) and then the border of this area was traced on a 1 mm grid paper and the squares inside this border were calculated. The manual measurement of the area was further confirmed by the use of a digital planimeter (Koizumi Sokki Mfg. Co. Ltd., Niigata, Japan). The reading on the 1 mm grid was adopted while the use of the digital planimeter was only intended to be a conformational step.

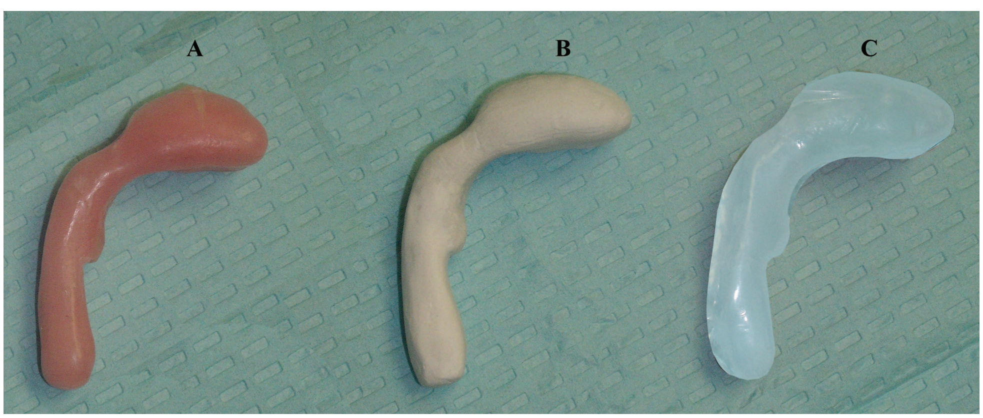

Figure 1 The airway model creation steps: (A) carved from wax, (B) poured into stone, and transferred into (C) air-filled soft acrylic model simulating the airway passage in shape and size.

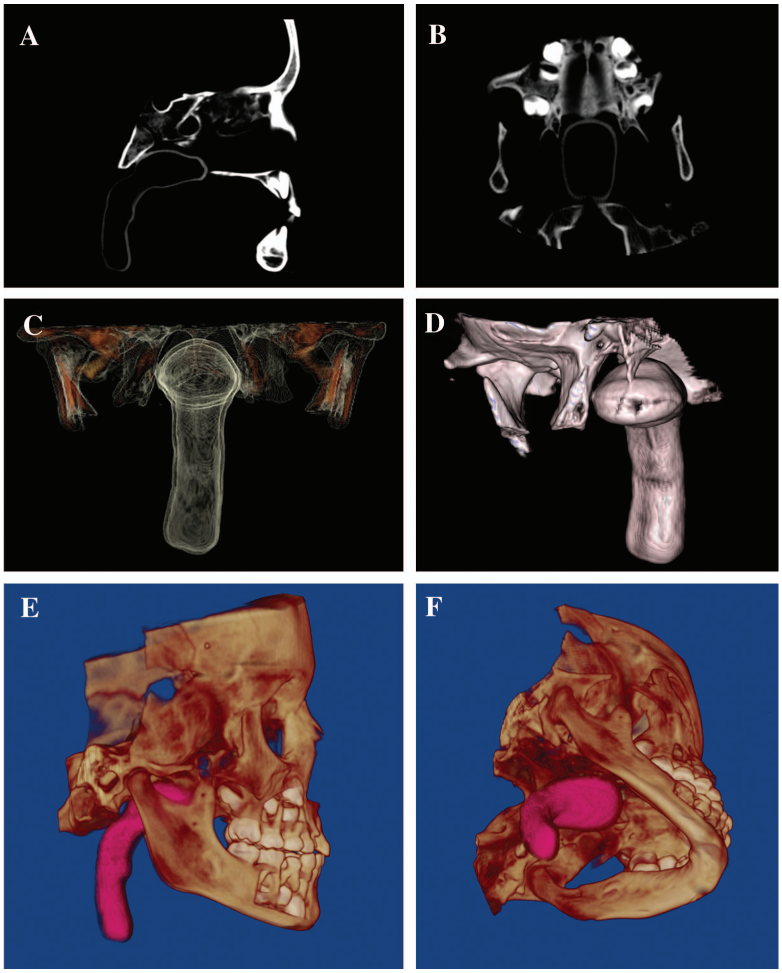

Figure 2 The airway model attached to the human dry skull in its natural position: (A) sagittal section, (B) axial section, (C–F) three-dimensional volume.

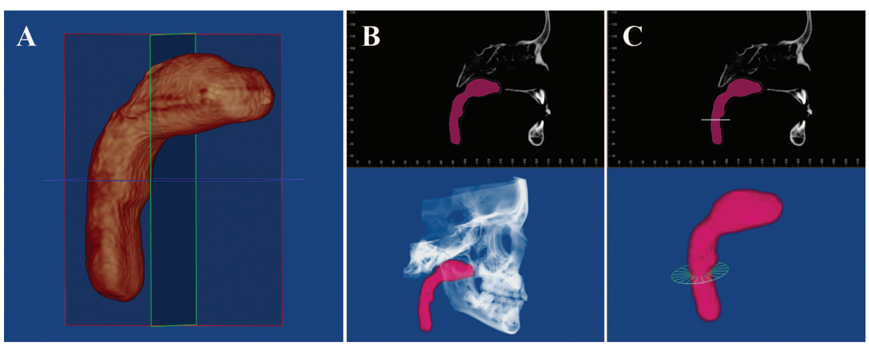

Figure 3 Digital measurements of the (A) total airway volume, (B) internal airway volume, and (C) the most constricted airway area.

The measurements were recorded 20 times over 20 days (once per day) by the primary investigator (AG) and then repeated 20 times 2 weeks later. The measurement errors were assessed by Dahlberg's method (Dahlberg, 1940) and the intraclass correlation coefficient (ICC) was used to assess intra-examiner reliability. The measurements were normally distributed; the mean and standard deviation were calculated and compared using Student's *t*-test. $P \leq 0.05$ was considered statistically significant. The mean difference between measurements was calculated as the mean manual measurements minus the mean CBCT measurements. Accordingly, negative value indicated that the manual measurement was smaller than the measurement made on CBCT scans. All statistical calculations were done using the computer programs Microsoft Excel 2010 (Microsoft Corporation, New York, New York, USA) and Statistical Package for the Social Sciences software (version 15; SPSS, Chicago, Illinois, USA).

Results

Intra-examiner reliability of both the manual and the CBCT method was high for all measurements, as indicated by ICC (≥0.90). The Dahlberg's values fell between 0.15 mm^2 for the CBCT measurement of the most constricted airway area and 0.98 mm^3 for the manual measurement of the total airway volume. Using *t*-test, no significant differences (*t*-test) were shown between the repeated measurements (Table 1). Comparison between the manual and the digital CBCT measuring methods showed no significant differences. The CBCT total and internal airway values overestimated the manual values slightly while the CBCT measurement of the most constricted airway area underestimated slightly the manual value (Table 2).

Discussion

Evaluation of the airway is useful in some orthodontic patients especially those with breathing disorders. The CBCT has been recently established as an orthodontic diagnostic modality. It has the advantage of high quality images and superior anatomic presentation with less radiation doses than the conventional CTs (Honey *et al.*, 2007). Moreover, the three-dimensional imaging systems allow the clinicians to overcome the limitations of the two-dimensional representation of three-dimensional objects. CBCT images have negligible magnification with a 1:1 ratio in all three planes of space (Lagravere *et al.*, 2011). However, these advantages still need to be weighed against the extra costs and higher radiation dose needed for using CBCTs. In addition, the reliability and accuracy of the CBCT images need to be investigated prior to introduction into clinical orthodontic practice.

Our approach was to investigate the accuracy of CBCT airway measurements by testing the actual volume of an airway model. This allowed us to compare the CBCT results with real volumetric measurements made directly on the model. The model constructed in this study compared well dimensionally and morphologically to a typical human airway according to data obtained from two-dimensional images measurements (Aboudara *et al.*, 2003; Preston *et al.*, 2004). The resulting dimensions of the model were further compared to dimensions recorded from studies on human subjects (Aboudara *et al.*, 2003; El and Palomo, 2010; Schendel and Hatcher, 2010) and confirmed that the model was an acceptable representation of a human airway.

The use of an airway model for evaluating accuracy and reliability of volumetric measurements in the present study eliminated the great variability that may occur when using

Table 1 Intra-examiner reliability for the manual and CBCT first and second series of the measurements presented as ICC and paired Student's *t*-test (*P*). CBCT, cone-beam computed tomography; CI, confidence interval; ICC, intraclass correlation coefficient; ME, measurement error (Dahlberg's values); SD, standard deviation.

Parameters	Manual (n = 20)						CBCT (n = 20)					
	Mean ± SD first	Mean ± SD second	Mean difference with 95% CI	ICC	ME	*P*	Mean ± SD first	Mean ± SD second	Mean difference with 95% CI	ICC	ME	*P*
Total airway volume (mm^3)	17576 ± 55.8	17583.5 ± 58.0	−7.50 (−12.51 to −2.49)	0.97	0.98	0.68	17590.8 ± 73.0	17597.9 ± 61.5	−7.11 (−20.76 to 6.54)	0.91	0.72	0.74
Internal airway volume (mm^3)	9581.5 ± 14.6	9582.5 ± 13.7	−1.00 (−3.59 to 1.59)	0.93	0.38	0.82	9587.19 ± 0.03	9587.2 ± 0.0	−0.01 (−0.02 to 0.04)	0.99	0.21	0.15
The most constricted airway area (mm^2)	71.8315 ± 1.4	71.8045 ± 1.5	0.03 (−0.28 to 0.33)	0.90	0.45	0.95	71.3 ± 0.04	71.3 ± 0.0	−0.01 (−0.03 to 0.01)	0.99	0.15	0.32

Significant at $P \leq 0.05$.

Table 2 Comparison between the manual and CBCT measurements (n = 20). CBCT, cone-beam computed tomography; CI, confidence interval; SD, standard deviation.

Parameters	Manual	CBCT	Mean difference with 95% CI	*P*-value
	Mean ± SD	Mean ± SD		
Total airway volume (mm^3)	17583.5 ± 58.0	17597.93 ± 61.5	−14.43 (−20.84 to −8.02)	0.45
Internal airway volume (mm^3)	9582.5 ± 13.7	9587.2 ± 0.01	−4.70 (−11.12 to 1.72)	0.13
The most constricted airway area (mm^2)	71.8045 ± 1.5	71.27 ± 0.01	0.50 (−0.20 to 1.21)	0.14

Significant at $P \leq 0.05$.

CBCTs of a real human airway. The variability results from changes in the airway position, morphology, and dimension due to the effects of either the patient's respiration or swallowing actions during the scanning procedure (Yildirim *et al.*, 1991; Battagel *et al.*, 2002). The reason for using the dry skull was to further simulate the human anatomy. The airway was attached to the skull in the exact position of the real human airway passage for the same reason. In addition, in this way, the model was easy to be scanned and, similar to a patient, the potential of overlapping bony structures could be replicated.

The choice of using a resin model was based on the fact that the acrylic resin is an easy to manipulate, soft, resilient, and transparent material. It allowed confirming that the model is totally filled by the water during the measurements steps. In addition, it retains its form and dimension after attaching it to the skull and during the scanning process and it provides a radiographically visual image.

In the present study, intra-examiner reliability was evaluated with correlation testing and indicated that the reliability was high for all measurements. We focused on repeated measurements of the same model and comparing the mean to eliminate the high variability in deriving a mean of a specific measurement on different models. No significant statistical difference was found between the total and internal airway volumes as well as the most constricted airway area measured on CBCTs compared with the manual measurements.

While many previous studies investigated the reliability of CBCT measurements of craniofacial and dental parameters, the literature is deficient in evaluating the reliability of airway measurements. Lagravere *et al.* (2008) and Baumgaertel *et al.* (2009) compared dental measurements generated on CBCT scans to the measurements made on a co-ordinate measuring machine using a synthetic mandible and to the measurements made directly on the dentitions of human dry skulls, respectively. Their results indicated that the CBCT measurements were reliable and accurate and supported the use of CBCT technology to analyse the dentition.

Studies concerning the reliability of the airway measurements on CBCTs compared them with data obtained from two-dimensional cephalograms. Aboudara *et al.* (2003) compared airway information from 11 normal adolescent children between lateral cephalometric headfilms and three-dimensional CBCTs. They concluded that intra-subject proportion of airway volume to area shows moderate variability and that CT airway volume shows more variability than corresponding headfilm airway area. They also indicated that there may be airway information that is not accurately depicted on the lateral headfilm. In their later study, Aboudara *et al.* (2009) compared imaging information about airway size between lateral cephalometric headfilms and three-dimensional CBCTs from 35 adolescent subjects. Their results indicated that there is a significant positive relationship between nasopharyngeal airway size on a headfilm and its true volumetric size from a CBCT scan. They concluded that the three-dimensional CBCT scan is a simple and effective method to accurately analyse the airway. Abramson *et al.* (2010) correlated the three-dimensional CT findings of airway size and shape with lateral cephalometric measurements. Their results indicated that the three-dimensional CT and lateral cephalometric measurements were reliable and reproducible. Vizzotto *et al.* (2011) evaluated the accuracy of airway measurements from lateral cephalograms, CBCT lateral reconstructions, and CBCT axial planes and correlated the findings with area measurements acquired with the latter imaging method. Their results showed that the airway linear measurements are reliable, with both lateral cephalograms and CBCT reconstruction, as there is a positive correlation with the respective area measurements on axial slices.

Yamashina *et al.* (2008) studied the accuracy of CBCT in measuring the density values of air, water, and soft tissues using a soft tissue equivalent phantom with different-sized holes. They indicated that the airway volume acquired from CBCT is nearly a one-to-one representation of the real volume and thus concluded that the measurement of the air space surrounded by soft tissues was accurate.

The results of the present study showed that the three-dimensional CBCT digital measurements of the airway volume and the most constricted area of the airway are reliable and accurate. These findings agreed with the results obtained by Schendel and Hatcher (2010) who studied the accuracy of automated three-dimensional airway analysis from CBCT data using a simulated airway phantom composed of a cylindrical air-filled plastic tube surrounded by water. No significant differences were found between the airway measurements obtained using the software program generated from the CBCT data and those obtained using the manual calculation methods. They concluded that measurement of the three-dimensional airway from CBCT data is accurate, reliable, and fast. The airway model used in the present study more closely resembled the natural airway.

Three-dimensional CBCT images offer accurate representation of the airway. In addition, the option provided by some softwares for detecting and measuring the most constricted area in the airway provides essential diagnostic clinical information in OSA patients. The results of the present study indicated the reliability of this technique in identifying the location and measuring the area of constriction although with slight insignificant underestimation. However, one of the limitations of this study is the simplicity of the shape of the constructed airway model compared with the intricate anatomy (especially the upper part) of the airway *in vivo*. Further studies are needed to determine inter-rater reliability in analysis of airway volumes and areas.

In conclusion, three-dimensional CBCT digital measurements of the airway volume and the most constricted area of the airway are reliable and accurate. The use of CBCT imaging for the assessment of the airway can provide clinically useful information in orthodontics.

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