Computerized measurement of the location and value of the minimum sagittal linear dimension of the upper airway on reconstructed lateral cephalograms compared to three-dimensional values

Introduction:

Upper airway assessment is an important component of orthodontic clinical examination given its influence on growth and craniofacial morphology. [1, 2] This in addition to its importance during orthodontic and orthognathic surgical treatment planning. [2]

Lateral cephalograms are records routinely obtained by orthodontists and for that reason, orthodontists are in a unique position to aid in early evaluation of the airway size and morphology, including the risk for obstructive sleep apnea (OSA). [3] To evaluate the sagittal airway dimension on a lateral cephalogram various measurements have been proposed such as: the posterior airway space, [4] the retropalatal airway space, [5] the superior posterior airway space, the middle airway space, and the inferior airway space. [6] Yet there is no consensus as to which of these measurements is the best approximation of the vertical location of the true minimum sagittal linear dimension (MSLD).

In addition to the conventional method to obtain lateral cephalograms, lateral cephalograms can also be obtained by reconstruction from a cone-beam computed tomography (CBCT) scan producing reconstructed lateral cephalograms (RLCs). Studies comparing the accuracy of linear and angular measurements using conventional cephalograms and RLCs found no significant differences between the two.[7, 8] Nevertheless, both lateral cephalograms remain a two-dimensional (2D) representation of a three-dimensional (3D) morphology. [8]

To analyze the upper airway three-dimensionally, the clinician can use magnetic resonance imaging (MRI), medical computed tomography, or CBCT, which is the current method of choice.[9] An important advantage of 3D imaging is to provide information about the exact location and nature of the airway obstruction in OSA patients which is crucial to obtain an effective treatment plan even in the presence of a sleep study. [10] However, the literature is lacking studies aimed to objectively identify the exact location and value of the MSLD in 2D images and to compare them to 3D measurements.

The objectives in the present study were: 1) to objectively identify the vertical location and the value of of the minimum sagittal linear dimension (MSLD) on 2D reconstructed lateral cephalograms (RLCs), 2) to compare the location and value of the MSLD on RLCs to the vertical location and sagittal dimension of the minimum cross-sectional area (MCSA) on CBCT scans, and 3) to investigate the association between the MSLD on RLCs and both the MCSA and the airway volume on CBCT scans.

Materials and Methods:

The sample of this retrospective study consisted of pre-treatment CBCT scans of orthodontic patients. The inclusion criteria were as follows: 1) age range of 10 – 80 years, 2) class I skeletal pattern with an ANB angle of 0°-5°, and 3) CBCT scans showing the entire fourth cervical vertebra. Patients with high mandibular plane angles (FMA >30° or SN-MP >40°), posterior cross-bites, previous orthopedic treatment, history of tonsillectomies or adenoidectomies, syndromes or craniofacial anomalies, history of OSA, and mouth breathers were excluded from the study. The University of Illinois at Chicago institutional review board reviewed and approved the study. A total of 1200 medical records were reviewed whereby 91 met the eligibility criteria and were analyzed. The sample was divided into three groups based on their age: under 20, 21 – 40, and over 40, with 30, 30, and 31 subjects per group respectively.

CBCT scans were taken as part of routine initial records in two private orthodontic offices operated by the same orthodontist. The CBCT devices were manufactured by the same manufacturer (I-CAT; Imaging Sciences International, Hatfield, Pa). The scans were obtained using the following settings: 120kV, 18.54 mAs, 16x13 field of view, 0.3 mm voxel, and 4.8 - 8.9 second scanning time. The patients were seated and the scans were taken in an upright position. Attempts were made to orient in natural head position using a mirror and a laser beam light and by having the Frankfort horizontal (FH) plane parallel to the floor. Patients were also instructed to breathe lightly through their noses, avoid deglutition, position the mandible in maximum inter-digitation, and rest the tongue in a relaxed position touching the anterior teeth.

The CBCT scans were obtained in Digital Imaging and Communications in Medicine (DICOM) format and were uploaded into Dolphin 3D software (Version 11.7, Dolphin Imaging, Chartsworth, CA). Dolphin 3D was used to orient and analyze the 3D images and to obtain reconstructed lateral cephalograms (RLCs).To orient the scans, guidelines proposed by Guijarro-Martinez and Swennen were adapted.[9] The skull was oriented to FH by defining the axial plane by three points: right porion, right orbitale, and left orbitale and checked in three reference views. On the right sagittal view, the horizontal reference line was fixed through porion and right orbitale (Figure 1A). On the frontal view, the horizontal reference line was fixed through the right and left orbitale, and the mid-sagittal plane was set through nasion and the anterior nasal spine (ANS) (Figure 1B). On the transverse view with the face facing down, the mid-sagittal plane was fixed through crista galli and basion (Figure 1C).

Following skull orientation, Dolphin 3D was used to automatically calculate the oropharyngeal airway volume, the minimum cross-sectional area (MCSA), the sagittal dimension of the MCSA (Figure 1D), and the vertical location of the MCSA measured from the level of the posterior nasal spine (PNS) in a plane perpendicular to FH (Figure 1E). The line measuring the sagittal dimension of the MCSA was centered in the MCSA transversely with care to assure this line was perpendicular to the coronal plane. Dolphin 3D utilizes a semi-automatic segmentation approach and an interactive threshold technique (one threshold value for the whole scan that is different from patient to patient). To segment the airway, the limits of the oropharynx were outlined (Table I) and a "seed" point was placed in the airway region. Additional "seed" points were placed as needed. The threshold was manually adjusted using a sliding scale function to maximize airway volume and minimize noise. The operator evaluated the airway slices in the sagittal, frontal, and transverse views to ensure appropriate threshold sensitivity. To limit extreme threshold variability, the threshold value was predetermined to be between 40 and 80. [9, 11] The threshold value for each CBCT scan was recorded.

Obtaining a 2D image was achieved by reconstructing a lateral cephalogram from the 3D scan. To account for the magnification error that occurs in conventional lateral cephalograms, the "perspective" projection function was used. RLCs were uploaded to Dolphin imaging software (version 11.0, Dolphin Imaging, Chartsworth, CA) to trace the oropharyngeal airway (tracing the inner margins of the surrounding borders) and to draw the palatal plane (ANS-PNS). All RLCs had a bar on the left hand side indicating 100 mm. The limits of this bar were identified in Dolphin using the points "Ruler Point 1" and "Ruler Point 2" after setting the ruler option to 100 mm in the setting section. This was done to insure calibration and standardization (Figure 2A).

Objective computerized measurement of the location and value of the minimum sagittal linear dimension (MSLD) was attained using a MATLAB™ mathematical software (MATLAB™ 8.4 (2014b), MathWorks, Natick, MA, USA) written by a software engineer specifically for this study. The written code assumed 100 mm ruler calibration, 1650x1275 pixels JPEG images and a resolution unit of 2. Adobe Photoshop CS5 (version 12.0.1, Adobe Systems Incorporated, San Jose, CA) was used to insure the required image size and resolution were appropriate before the images were uploaded to MATLAB. Once in MATLAB, the image was calibrated by identifying Ruler Points 1 and 2, point PNS was identified, and the posterior and anterior borders of the oropharyngeal airway were retraced. The software calculated the MSLD by identifying the smallest distance between the anterior and posterior borders of the airway. The software also calculated the vertical distance of the MSLD to PNS in a plane perpendicular to FH. Both measurements were generated in millimeters up to the 4^{th} decimal place (Figure 2B).

Measurements for 15 scans, both 3D and 2D, were performed by the principal investigator then repeated 15 days later by the principal investigator and a second assessor to determine the intra-rater and inter-rater reliability. Intraclass correlation coefficient was used to test reliability. The distribution of the raw data was investigated using Shapiro-Wilk test of normality. Correlation coefficient tests were used to test the association between the vertical location and value of the MSLD on the RLCs and the sagittal dimension and the vertical location of the MCSA on the CBCT. Correlation coefficient tests were also used to investigate the association between the MSLD on the RLCs and both the MCSA and the volumetric airway measurements on the CBCT. Parametric and nonparametric tests, Pearson and Spearman, were used as needed. Statistical significance was noted at $\alpha = .05$. When evaluating the strength of correlation, the following classification was used: strong if $0.7 < |r| \leq 1.0$, moderate if $0.4 \leq |r| \leq 0.7$ and weak if $0.2 < |r| < 0.4$.

To further investigate the agreement between the vertical location and value of the MSLD on the RLCs and the vertical location and the sagittal dimension of the MCSA on the CBCT, Bland-Altman plots were used.[12] Visual inspection of the plots, including the bias and the 95% limits of agreement, were performed to evaluate the reliability of the 2D measures relative to the 3D measures. Data analysis was done by IBM SPSS Statistics for Windows, Version 22.0, (Armonk, NY: IBM Corp.).

Results

The ages of the subjects ranged from 11.1 to 75.8 years with a mean age of 31.48 ± 17.55 years. Of the 91 subjects, 45 (49.45%) were male and 46 (50.55%) were female, with equal gender representation in each of the three age groups. The threshold values for the CBCT scans ranged from 40 to 60 with a mean of 47.22 ± 5.53. Intraclass correlations showed strong correlations (r>0.80) indicating reliability. Table II shows descriptive statistics of the 2D and 3D measurements.

There were significant correlations between the vertical location of the MSLD on the RLCs and the vertical location of the MCSA on the CBCT scans (Figure 3), and between the MSLD on the RLCs and the sagittal dimension of the MCSA on the CBCT scans (Figure 4). Significant correlations were also seen between the MSLD on the RLCs with both the MCSA and the oropharyngeal airway volume on the CBCT scans in all three age groups. Table III shows the results of the correlation tests with Pearson and Spearman coefficients of correlation.

Bland-Altman analyses for the vertical locations of the MSLD and the MCSA are displayed in figure 5. The mean differences and 95% limits of agreement were -2.3 mm (-23.8, +19.2), -2.11 mm (-28.14, +23.92), and -0.27 mm (-24.12, +23.58) for age groups 1, 2, and 3 respectively. Bland-Altman analyses for the MSLD and the sagittal dimension of the MCSA are displayed in figure 6. The mean differences and 95% limits of agreement were -1 mm (-4.88, +2.88), -2.01 mm (-6.4, +2.38), and -1.16 mm (-6.14, +3.82) for age groups 1, 2, and 3 respectively.

Discussion:

The use of CBCT as a 3D diagnostic tool is increasing because of its advantages over medical CT and MRI. CBCT has much lower radiation when compared to medical CT and shorter acquisition time compared to MRI. Additionally, when compared to both medical CT and MRI, CBCT has the advantage of having lower cost and easier access.[9, 10, 13, 14] Important information obtained from a CBCT scan include the vertical location of the MCSA, which is essential for treatment planning of OSA patients,[10] and the MCSA itself, which has been shown to be correlated with the respiratory disturbance index (RDI) [15] and OSA severity [16]. In this study, we sought to find out how effective a 2D image would be in finding the vertical location of the MCSA and how meaningful is the MSLD.

Previous studies have demonstrated that the upper airway soft tissues differ when subjects are asleep as opposed to awake, [17] and when they are in the supine position as opposed to the upright position [7] The scans included in the present study were taken with the patients awake and in an upright position. This resembles how radiographic records are taken and the upper airway is screened in an orthodontic office. Additionally, in the present study we chose to limit our evaluation to the oropharynx as has been previously described [18] since most airway constrictions in adults occur in the oropharynx. [6, 16] It is worth mentioning that although we did not include the nasopharynx due to its complexity, [19] the nasopharynx becomes very important clinically in children considering adenoidectomy and tonsillectomy is the first line of treatment in children diagnosed with OSA.[20] However, the mean age for age group 1 in our sample was 13.90 ± 1.60 years which is an age at which the adenoids have decreased in size and continue to decrease. [21]

The results of this study showed that there were significant moderate correlations between the vertical location of the MSLD on the RLCs and the vertical location of the MCSA on the CBCT scans. Further analysis using Bland-Altman analyses (Figure 5) showed that the mean differences between the vertical location of the MSLD on the RLCs and the vertical location of the MCSA on the CBCT scans for the different age groups ranged from -0.27 to -2.3 mm. However, the 95% limits of agreement were very wide extending to and beyond -20 and +20 mm making 2D images not very reliable at finding the vertical level of the MCSA.

Similarly, there were significant correlations between the MSLD on the RLCs and the sagittal dimension of the MCSA on the CBCT scans. These correlations were strong for age groups 1 and 2. (Table III). Bland-Altman analyses (Figure 6) showed that the mean differences between the MSLD on the RLCs and the sagittal dimension of the MCSA on the CBCT for the different age groups ranged from -1 to -2.01 mm. Furthermore, and in contrast to the vertical location, the Bland-Altman 95% limits of agreement were not as wide ranging from about -6 to 4 mm. This in addition to the stronger correlation makes 2D images much more reliable at identifying the sagittal dimension compared to the vertical level of the MCSA.

The sagittal dimension Bland-Altman plots showed that the MSLD was consistently smaller than the sagittal dimension of the MCSA (Figure 6).This can be explained by the fact that the sagittal dimension of the MCSA on the CBCT at a specific level may not be the absolute minimum sagittal dimension of the airway. For example, there could have been other cross-sectional areas with smaller sagittal dimensions yet larger transverse dimensions resulting in larger cross-sectional areas than the MCSA and hence not identified. Nevertheless, the mean sagittal difference was about 1.5 mm and it is at the discretion of the clinician to determine if this difference is clinically significant

Though there are various proposed measurements to evaluate the sagittal airway dimension in 2D images, [4-6] we decided to objectively measure the minimum sagittal linear dimension using a customized software. In addition to the MSLD showing significant correlations with the sagittal dimension of the MCSA, our results showed significant correlations between the MSLD and both the MCSA and the airway volume in all age groups. Correlations were weaker for airway volume and this is comprehensible since the literature shows airway volume to have larger variability when compared to the MCSA and its sagittal dimension and, is therefore, less meaningful.[16]

Lately 2D images have been disregarded as an airway evaluation tool and CBCT has gained popularity due to its advantages over medical CT and MRI. Yet we must not forget that conventional lateral cephalograms have these same advantages over CBCT, namely lower radiation, lower cost, easier access, and shorter acquisition times and should be utilized as applicable. [22] A CBCT scan with 13 x 16 cm field of view taken with standard exposure parameters exposes adults and children to 85 and 120 micro-Sieverts of effective dose respectively. This radiation exposure is 20 to 30 times that of a conventional lateral cephalogram which is about 4 micro-Sieverts.[23] Given our results, the fact that studies have shown no significant differences between RLCs and conventional cephalograms, and the advantages of conventional cephalograms over CBCT, we believe that conventional cephalograms should not be discarded as an airway screening tool.

Evaluation of the location and value of the MSLD in this study was performed objectively using a customized software and further research is in progress to evaluate how objective evaluation of these values compares to subjective evaluation. Finally, even though the MSLD showed significant moderate to strong correlation with the MCSA and its sagittal dimension, more research is needed to investigate the clinical significance of the MSLD as it relates to OSA.

Conclusions:

There were significant correlations between the MSLD and each of the sagittal dimension of the MCSA, the MCSA, and the airway volume in all age groups. Moreover, Bland-Altman plots showed 2D images to be more reliable at finding the sagittal dimension of the MCSA compared to finding the vertical location of MCSA which had very wide limits of agreement in all age groups.

Although comprehensive assessment of airway characteristics is better achieved with CBCT-based 3D evaluation, useful information can be obtained from 2D lateral cephalograms. The MSLD can be a useful measure in screening for OSA patients.

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Figure Captions:

Figure 1. (A) Skull orientation right sagittal view; (B) Skull orientation frontal view; (C) Skull orientation transverse view; (D) Sagittal dimension of the minimum cross-sectional area; (E) Vertical location of the minimum cross-sectional area. Images rendered using Dolphin (dolphinimaging.com).

Figure 2. (A) Tracing and bar indicating 100 mm for calibration (image rendered using Dolphin (dolphinimaging.com); (B) Location and value of the minimum sagittal linear dimension calculated using MATLAB.

Figure 3. Correlations between the vertical location of the MSLD and the vertical location of the MCSA in age groups 1, 2, and 3.

Figure 4. Correlations between the MSLD and the sagittal dimension of the MCSA in age groups 1, 2, and 3.

Figure 5. Bland-Altman analyses for the vertical locations of the MSLD and the MCSA for age groups 1, 2, and 3.

Figure 6. Bland-Altman analyses for the MSLD and the sagittal dimension of the MCSA for age groups 1, 2, and 3.