Relationship Between Nostril, Nasal Valve and Minimal Cross-Sectional Area in Functional Upper Airway

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Purpose: To propose a three-dimensional cephalometric analysis of upper airway (UA) related to its functionality, defining normal reference values in healthy individuals and the relationship between nostril, nasal valve, and minimal cross-sectional area (MCS) in functional upper airway.

Materials and Methods: The UAs of 20 Class I patients were analyzed with CBCT using Nemoceph 3D-OS and HOROS software, determining linear distances, volumes and cross-sectional areas, including MCS.

Results: MCS was mostly located in the middle-upper oropharynx and high hypopharynx. MCS showed moderate correlation with the area of both nares (BNA) ($r = 0.60$, $P = 0.004$) and high correlation with the area of both internal nasal valves (BNV) ($r = 0.66$, $P = 0.0016$). BNA and BNV showed a moderate correlation ($r = 0.445$, $P = 0.049$). A total upper airway (TUA) and functional upper airway (FUA) volumes were established. TUA and FUA showed the strongest statistical correlation ($r = 0.82$, $P = 0.00$). A paired samples t test compared the measurement as absolute values of MCS with BNA ($t = 0.781$, $P = 0.44$), with BNV ($t = -0.12$, $P = 0.90$); and BNA with BNV ($t = -0.76$, $P = 0.45$), showed no significant differences.

Conclusions: A functional cephalometric analysis of the UA with stable parameters in cervical spine and normal reference values has been proposed. BNA and BNV could be used as reference to establish the MCS compatible with respiratory health.

Key Words: Cephalometry, cone beam computed tomography, obstructive sleep apnea syndrome, upper airway

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The configuration and dimensions of the pharyngeal upper airway (UA) are determined by the anatomical structures that surround the pharynx, both soft tissue as well as the cranio-cervical-facial skeleton. The upper airway is composed of the nasal and oral cavities, pharynx, and larynx. The pharynx is usually classified in 3 areas: nasopharynx, oropharynx and hypopharynx. Bilaterally, the nasal cavity is represented by the nasopharynx.[1] The nasopharynx is located behind the nasal cavity and above the soft palate, then continues downward with the oropharynx. The oropharynx is located behind the oral cavity and above the epiglottis. The hypopharynx is located below the epiglottis and extends to where this common path diverges into the respiratory (larynx) and digestive (esophagus) ways.

Any anatomical anomaly can modify the pharyngeal airway space and potentially constitute an etiological factor of respiratory pathologies, like an obstructive sleep apnea/hypopnea syndrome (OSAS). In the same sense, surgical procedures like an orthognathic surgery and other complementary techniques also affect the size and position of the UA soft tissues, with varying degrees of impact on the respiratory function.

Several studies have validated the use of cone beam computed tomography (CBCT) for studying the UA, arguing that it is a highly effective method compared with conventional radiographic techniques.[1–7] The cephalometric analysis using CBCT and the different commercial software available have the advantage of allowing a more complete and precise three-dimensional approach to the UA, reducing working time, facilitating manipulation of images and the acquisition of the volumes, areas, and linear distances accurately. However, the published articles use different criteria for analyzing the UA and, for this reason, present difficulties both in terms of methodology as well as the applicability of their results. On the one hand, they use diverse anatomical references to subdivide the UA and, therefore, measure lengths, cross-sectional areas and volumes of these regions differently depending on the studies question, which makes comparisons among them difficult and weakens the available evidence. In addition, these anatomical reference points are sometimes modified with surgical interventions like orthognathic surgery and, for this very reason, even considering each study individually, there is no way to guarantee that the volumetric changes in the UA correspond to a real variation in their pre- and post-surgical dimensions, or if the differences observed are explained by the use of parameters that change spatially with surgery and, therefore, the measurements, areas and volumes calculated based on them to vary as well.

Another shortcoming in the majority of studies related to UA is that they do not consider the nose as an anatomical region of analysis, despite the fact that it accounts for 50% of the total airway resistance. The greatest resistance inside the nose is located in the area of internal nasal valve, bounded by the caudal edge of the upper lateral cartilage and the septum,[8] which causes approximately 70% of the nasal resistance, with the remaining 30% being produced in the turbinal region.[9]

The goals of this study are: 1) to propose a three-dimensional cephalometric analysis of the UA focusing on its functional aspect

(Fariña Functional Airway Cephalometric Analysis, FACA), defining stable anatomical reference parameters in the cervical spine and not modifiable with surgical interventions in the maxillofacial region; 2) to determine normal linear distances, volumes and cross-sectional areas for the UA, including the minimal cross-sectional area (MCS) in healthy patients using the proposed cephalometric analysis and 3) to compare the MCS of the upper airway with the area of both nares (BNA) and the area of both internal nasal valves (BNV) to determine whether there is a relationship between them.

MATERIALS AND METHODS

Patients

A cross-sectional observational study was designed in compliance with the Helsinki Declaration. The medical records of patients who consulted for orthodontic treatment in private practice, to whom a CBCT was requested as a complementary examination for definitive diagnosis, were reviewed.

Patients with a Class I skeletal pattern were selected, considering the SNA, SNB and ANB angles within normal ranges. The Epworth daytime sleepiness scale was applied to them to facilitate the diagnosis of sleep disorders, as well as a general health survey to know about sleep habits, nutritional status and respiratory pathologies.

The inclusion criteria were: adult patients of both genders, over 15 years old, healthy, without respiratory or sleep-related pathologies, Class I skeletal pattern.

Exclusion criteria were: the presence of craniofacial anomalies, respiratory and pharyngeal pathologies, snoring, obstructive sleep apnea/hypopnea syndrome or other sleep disorders, a medical history of previous airway surgery or orthognathic surgery, obesity (BMI > 28) and CBCT with incomplete images of the UA.

The sample was composed of 20 patients who fulfilled the inclusion criteria and who signed the informed consent authorizing use of their CBCTs.

Image Acquisition

All CBCTs were performed at a private imaging center, in Santiago de Chile, between 2015 and 2017. The images were obtained using a Kodak 9500 Cone Beam 3D System (Carestream Health Inc., Rochester, NY) tomograph operating at 90 kV, 10 mA, with a 0.2 mm^3 voxel and a 9 × 15 cm field of view (FOV). The CBCTs were taken with the patients seated, with Frankfort plane parallel to the floor, at maximum intercuspation, without swallowing, holding their breath at the end of exhalation, without moving during exposure.

Analysis of Images and Anatomical Reference Parameters

Digital image files of each patient were exported in Digital Imaging and Communication in Medicine (DICOM) format and imported to Nemoceph 3D-OS software (Nemotec Software SL, Madrid, Spain) and HOROS software (FOSS, Horosproject.org, NIMBLE Co LLC, Annapolis, MD). The patients' heads were reoriented based on the horizontal Frankfort reference plane, the mid-sagittal plane and the transporionic plane[10] in both programs.

The same researcher (AG) evaluated the CBCT images and the measurements. To create the UA model in this study, the imported images were segmented and individually adjusted considering the gray scale to delimit the air-soft tissue-bone tissue interface. The anatomical reference points, limits and parameters of the UA evaluated in this study are described in Table S1 (see Supplemental Digital Content, http://links.lww.com/SCS/A725) and Fig. 1A–C. The upper boundary of the UA was defined at the level of a parallel line to Frankfort horizontal plane (FH) passing through the highest point of the body of the atlas (A), in the mid-sagittal plane. The lower boundary of the UA was defined at the level of a parallel line to FH which passes through the anterosuperior vertex of the body of the fifth cervical vertebra (5CV), in the mid-sagittal plane. Posterior boundary was the posterior pharyngeal wall (PPW) and anterior boundary was composed of soft palate, tongue, anterior pharyngeal wall and larynx.

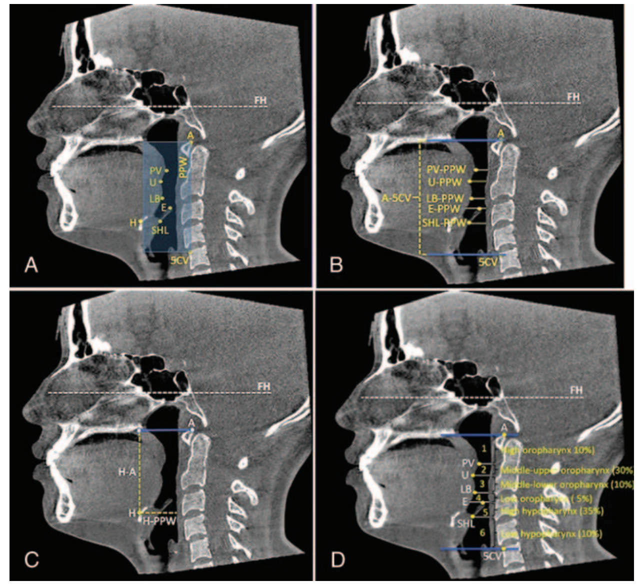

FIGURE 1. (A) UA reference points and boundaries, defined on the mid-sagittal plane. Upper Limit: line parallel to the Frankfort horizontal (FH), passing through the upper atlas point. Lower Limit: line parallel to the FH which passes through the anterosuperior vertex of the body of the fifth cervical vertebra. Posterior Limit: posterior pharyngeal wall (PPW) and Anterior Limit: soft palate, tongue, anterior pharyngeal wall and larynx. (B) Linear distances and cross-sectional areas, measured in: PV, U, LB, E and SHL. A-5CV corresponds to the UA height. (C) Linear distance from the hyoid bone to the upper limit (H-A) and the posterior limit (H-PPW) of the UA. (D) UA subdivision for this study. The regions were defined as: 1) high oropharynx (between A and PV), 2) middle-upper oropharynx (between PV and U), 3) middle-lower oropharynx (between U and LB), 4) low oropharynx (between LB and E), 5) high hypopharynx (between E and SHL) and 6) low hypopharynx (between SHL and 5CV).

The Nemoceph 3D-OS software allowed measuring linear distances, cross-sectional areas and taking volumetric measurements of the UA. The HOROS software was used to measure the cross-sectional area of both nares (BNA) and both internal nasal valves (BNV) following the protocol of Schriever et al[11] (Fig. 2A) and Bloom et al[12] (Fig. 2B), respectively.

Nemoceph 3D-OS software automatically provides the location and measurement of the MCS area of the UA. To register the specific sector of the UA where the narrowest area is located, the UA was vertically subdivided into 6 regions, drawing horizontal lines parallel to FH in the mid-sagittal plane, at the points: posterior velar (PV), uvula (U), lingual base (LB), epiglottis (E), and hyoid at the soft tissue level (SHL). The regions were defined as: high oropharynx (between A and PV), middle-upper oropharynx (between PV and U), middle-lower oropharynx (between U and LB), low oropharynx (between LB and E), high hypopharynx (between E and SHL) and low hypopharynx (between SHL and 5CV) (Fig. 1D).

The following parameters of the UA were measured: 1) Horizontal linear distances on the mid-sagittal plane from the landmarks

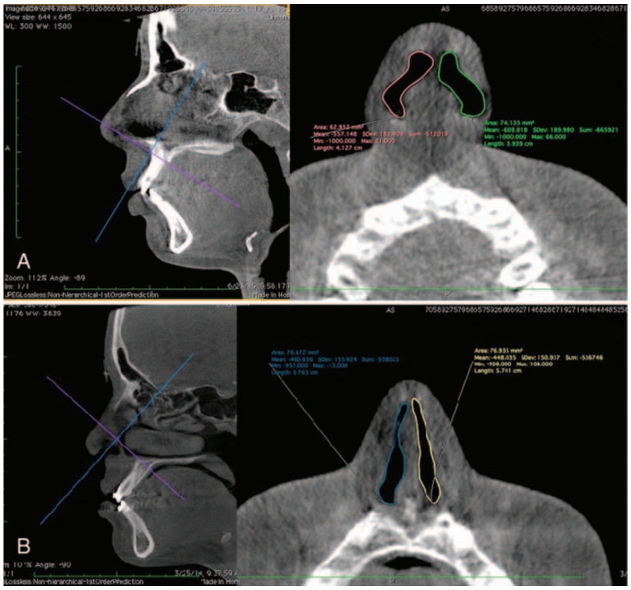

FIGURE 2. (A) Measurement of cross-sectional area in nares, following the Schriever et al protocol. (B) Measurement of cross-sectional area and angle of the internal nasal valve angle, following Bloom et al protocol.

(PV, U, LB, E and SHL) to posterior pharyngeal wall (PPW): PV-PPW, U-PPW, LB-PPW, E-PPW, SHL-PPW; 2) Vertical linear distance (UA height) between A and 5CV (A-5CV); 3) Cross-sectional areas in PV-PPW, U-PPW, LB-PPW, E-PPW, SHL-PPW, BNA, BNV, and MCS; 4) Total upper airway volume (TUA) and functional upper airway volume (FUA, calculated by multiplying the minimal cross-sectional area by the UA height (MCS × A-5CV)); 5) the position of the hyoid bone: horizontal hyoid (H-PPW) and vertical hyoid (H-A) (see Table S1, Supplemental Digital Content, http://links.lww.com/SCS/A725).

Statistical Analysis

All data was obtained by the same investigator (AG) and entered into Microsoft Excel spreadsheet. The data was analyzed using Stata IC software (version 15, StataCorp, LLC). A descriptive statistical analysis was performed, including averages and standard deviations for each variable. The Shapiro-Wilk test was used to determine normality in the distribution of variables. A linear regression analysis was performed to determine if there was correlation between the variables: MCS with BNA, MCS with BNV, BNA with BNV, and TUA with FUA. The correlation was interpreted as: from 0 to 0.20 indicates a very low correlation; 0.21 to 0.40 poor correlation; 0.41–0.60 moderate correlation; 0.61 to 0.80 a strong correlation and >0.80 the strongest correlation. A paired samples *t* test was also used to compare the measurements as absolute values of variables MCS with BNA, MCA with BNV, BNA with BNV and TUA with FUA. A value of $P \leq 0.05$ was considered statistically significant for all analyses.

RESULTS

The descriptive statistics of the variables under study are shown in Table S2 (see Supplemental Digital Content, http://links.lww.com/SCS/A725). The distribution of variables was normal, except for BNV ($W = 0.893$, $P = 0.031$).

Regarding location of the MCS of the UA, the majority were located in the middle-upper oropharynx (region 2) and the high hypopharynx (region 5), with 30 and 35%, respectively (see Table S3, Supplemental Digital Content, http://links.lww.com/SCS/A725).

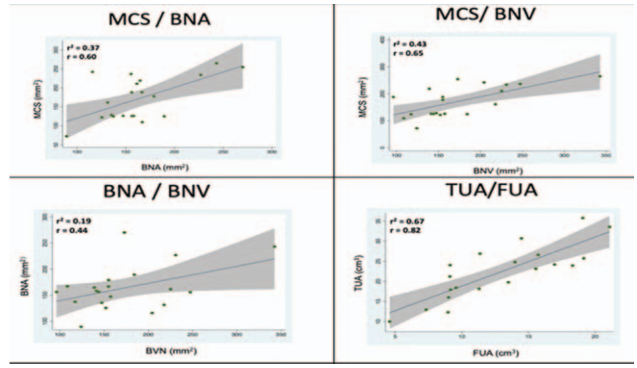

FIGURE 3. Linear regressions scatter plots and Pearson coefficient of the UA parameters studied.

The MCS showed a statistically significant moderate correlation with BNA ($r = 0.60$, $P = 0.004$), a high correlation with BNV ($r = 0.66$, $P = 0.0016$). BNA and BNV showed a statistically significant moderate correlation ($r = 0.445$, $P = 0.049$). TUA and FUA showed the strongest statistical correlation ($r = 0.82$, $P = 0.00$) (Fig. 3).

A paired samples *t* test showed no significant differences ($P > 0.05$) when comparing the measurements as absolute values of MCS with BNA ($t = 0.781$, $P = 0.44$), MCS with BNV ($t = -0.12$, $P = 0.90$), and BNA with BNV ($t = -0.76$, $P = 0.45$). When comparing TUA and FUA there was statistically significant difference ($t = 10.45$, $P = 0.00$) (see Table S4, Supplemental Digital Content, http://links.lww.com/SCS/A725). The proportion between BNA/MCS/ was 0.953, while BNV/MCS was 1.002. Both almost relating one to one.

DISCUSSION

This study proposes a three-dimensional and functional airway cephalometric analysis of the UA (FACA), using a CBCT to generate images in the 3 planes of space to measure linear distance, cross-sectional areas and volumetric measurements of the entire UA. Regarding this, numerous studies have been published in which CBCT is used to evaluate the upper airway and some of them have established the precision and reliability of the measurements obtained.[7,13,14]

Quantitative and qualitative changes in the UA during the different phases of respiration have been discussed in the literature[15,16] and the influence of position of the head, tongue, and jaw position on the shape and size of the oropharyngeal airway.[5] The studies evaluating the UA usually measure volumes, cross-sectional areas and linear distances pre- and post-orthognathic surgery, mono- or bimaxillary, in Class II and III patients diagnosed with OSAS. The patients in this study were healthy, Class I skeletal pattern, without respiratory, sleep disorders or surgical interventions in the UA, and the CBCT capture was standardized in an effort to minimize the risk of bias in measurements and to determine normal UA values.

One of the problems with the articles studying the UA is the definition of its anatomical boundaries and reference points for measurement. Furthermore, some of the parameters described are modified with surgical techniques such as orthognathic surgery.[2,4,6,7,17] This is particularly important when evaluating patients with respiratory and sleep disorders in the preoperative and postoperative lapse, since it is not possible to accurately determine if the volumetric variations observed in the UA are real or there is a systematic error in interpreting the results obtained. Along these same lines, the studies published are very inconsistent in the anatomical definitions that they use. It is, therefore, methodologically impossible to make comparisons and very difficult to combine data to obtain normal UA values.

The study attempts to overcome these difficulties by using stable reference parameters in the cervical spine to define the limits of the upper airway. For example, the posterior nasal spine is not used as an upper or anterior boundary of the UA, given it is usually displaced in an anterior and/or vertical direction with surgery. The atlas point was used as an alternative, since it was considered a stable point and one easily recognized in the CBCT.

The lower limit is defined at the level of the anteroinferior vertex of the fifth cervical vertebra, which has the advantage of being easily and accurately located in the CBCT and is an area where the effects of mandibular displacement are no longer represented. Thus, the total UA volume (TUA) will always be comparable before and after surgery, since the anatomical reference parameters used to determine it are stable in the cervical spine and unmodifiable by surgical interventions in the maxillofacial area.

The minimal cross-sectional (MCS) area of the UA is very important when evaluating patients who are candidates for ortho-surgical treatment, because of its role in OSAS.[3,18] Although the polysomnography is the gold standard for OSAS diagnosis, this test cannot detect the precise location of the airway obstruction. Nasal endoscopy is a useful tool, along with magnetic resonance and computed tomography.[19] However, this study shows how simple it is to determine the narrowest areas of the UA using CBCT with the appropriate software, reducing costs and radiation exposure in a less invasive and easily accessible way.

This study determined the location of the MCS (see Tables S2 and S3, Supplemental Digital Content, http://links.lww.com/SCS/A725). In addition, according to Poiseuille Law ($R = 8L\eta/\pi r4$; where R is the resistance, L is the length of the tube, η is the viscosity and r is the radius of the tube), the radius is the most important factor of flow resistance in the airway. The UA has anfractuous features that determine broad areas and others that are narrower. Adapting Poiseuille Law to this study of the UA, the MCS would have the smallest radius and, therefore, this area would constitute the critical factor for airflow resistance, as the radius would be raised to the fourth power and be inversely proportional to the resistance. This allows the concept of functional upper airway (FUA) to be introduced, which is the volume obtained by multiplying the MCS (mm^2) by the vertical distance A-5CV (mm), which is related to respiratory physiology and resistance to the airflow in the UA. That is why the place where the MCS is located and its quantification should guide the ortho-surgical treatment plan in order to expand this narrower area. This can make a real impact on respiratory function, especially in patients with OSAS. The increase of TUA without a significant expansion in MCS and FUA could imply a failure in the reduction of UA resistance and a poor clinical outcome after surgical treatment.

This study determined the area of the nares and internal nasal valves bilaterally. This is because the nose is the gateway to the upper airway, and at level of the internal nasal valve is where its greatest resistance is described. A positive correlation between MCS, BNA and BNV was found. No significant differences were found when comparing MCS with BNA and BNV. Since the group of patients studied is composed of healthy individuals, this could be interpreted as a consistency in terms of resistance throughout the entire UA; that is, similar cross-sectional areas and airflow resistance in MCS, BNA and BNV. BNA and BNV can be used as a reference regarding the minimum objective to be achieved with the surgical treatment of patients with OSAS. In the same sense, it could be inferred that if a patient has a MCS greater than BNA and/or BNV, he would not be candidate for surgical correction with orthognathic surgery.

CONCLUSIONS

CBCT improves the ability to determine volumetric dimensions, linear distances and cross-sectional areas of the UA when compared to conventional 2D radiology.

A three-dimensional and functional cephalometric analysis of the upper airway (Fariña Functional Airway Cephalometric Analysis, FACA) is proposed, using CBCT on patients with skeletal Class I, without general pathologies or sleep disorders.

Normal reference values for the parameters studied are shown, with the following standing out: $TUA = 22.29\,cm^3$, $DS = 6.82\,cm^3$; $FUA = 12.86\,cm^3$, $DS = 4.57\,cm^3$; $MCS = 171.84\,mm^2$, $DS = 56.98\,mm^2$; $BNA = 163.81\,mm^2$, $DS = 42.82\,mm^2$ y $BNV = 173.14\,mm^2$, $DS = 58.00\,mm^2$.

The proposed cephalometry is easy to perform and has the advantage of using stable and non-modifiable reference points with surgery for calculating the total and functional volume of the upper airway.

It is important to determine the location and quantify the MCS for an adequate diagnosis and to guide the ortho-surgical treatment, especially in patients with sleep disorders. For the study group, the MCS was mostly located in the middle-upper oropharynx (region 2) and the high hypopharynx (region 5), with 30 and 35%, respectively.

The concept of FUA is introduced, volume obtained by multiplying the MCS (mm^2) by the vertical distance A-5CV (mm), which is related to respiratory physiology and resistance to the airflow in the UA. An increase in the UA following orthognathic surgery should be expressed as an increase in FUA, to be clinically significant.

It has been established that there is a statistically significant moderate/high correlation between MCS with BNA and MCS with BNV. TUA and FUA showed the strongest statistical correlation. As absolute values, a statistical equality between MCS, BNA, and BNV in the UA was shown. BNA and/or BNV could eventually be used as references to establish the MCS compatible with respiratory health.

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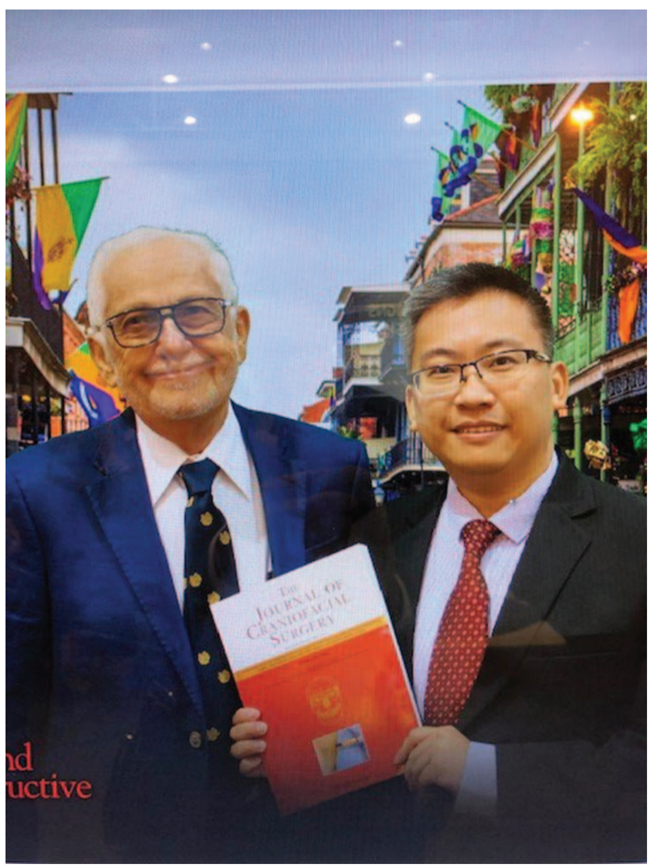

Think fat...fat is beautiful.