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ORIGINAL ARTICLE

MG Lenza
MM de O. Lenza
M Dalstra
B Melsen
PM Cattaneo

An analysis of different approaches to the assessment of upper airway morphology: a CBCT study

Authors' affiliations:
M.G. Lenza, M.M. de O. Lenza, Instituto Lenza, Goiânia, Brazil
M.G. Lenza, M.M. de O. Lenza, M. Dalstra, B. Melsen, P.M. Cattaneo, Department of Orthodontics, School of Dentistry, Faculty of Health Science, University of Aarhus, Aarhus, Denmark

Correspondence to:
Paolo M. Cattaneo
Department of Orthodontics
School of Dentistry
University of Aarhus
Vennelyst Boulevard 9
DK-8000 Aarhus C
Denmark
E-mail: pmcattaneo@gmail.com

Structured Abstract

Authors – Lenza MG, Lenza de O MM, Dalstra M, Melsen B, Cattaneo PM

Background – Upper airway morphology and respiration have been assigned an important role in the development of the craniofacial complex. Several studies advocate lateral cephalograms to evaluate the upper airway. Although this method has been widely used, a two-dimensional projection of a three-dimensional anatomical structure is questionable.

Objective – To correlate linear measurements (sagittal and transversal), cross-sectional areas, and volumes of the upper airway determined on Cone Beam CT (CBCT) data sets.

Material and Methods – CBCT-scans of 34 patients were used to perform a 3D evaluation of the upper airway. Linear sagittal measurements reproducing those usually performed on lateral cephalograms, linear transversal measurements, cross-sectional areas, partial and total volumes (TV) were computed.

Results – The analysis showed a weak correlation ($r < 0.8$) between most of the linear measurements. The correlations between sagittal, transversal, and cross-sectional area with partial volumes were weak, except for the lower part of the nasopharynx which was highly correlated ($r > 0.9$) with sagittal measurement and with area. The upper part of the velopharynx presented a good correlation ($0.8 < r < 0.9$) between area and volume. Good correlation between most transversal measurements and the corresponding areas was found. Minimal sagittal, minimal transversal, and minimal area were weakly correlated with TV.

Conclusions – Upper airway cannot be accurately expressed by single linear measurements as performed on cephalograms. The TV alone does not depict the morphology of the airway. A CBCT-based 3D analysis gives a better picture of the anatomical characteristics of the upper airways and therefore can lead to an improvement of the diagnosis.

Key words: cephalometry; measurement; tomography; upper airway

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Introduction

Since the introduction of the cephalostat, linear and angular measurements performed on lateral headfilms have been the method of choice when exploring craniofacial development, including nasorespiratory function. The interest in airways on craniofacial growth peaked in the

1970s where a multidisciplinary team described the problems from various points of view such as neuromuscular adaptations, nasopharyngeal obstruction, growth, breathing, and speech (1). This topic was later addressed by Warren and Spalding (2) who stated that the relationship between nasorespiratory function and dentofacial development remains controversial, and that radiographic evidence of airway is questionable. Obviously, 2-dimensional (2D) measurements do not render well the complex airway morphology and might overlook much of the anatomical information necessary to make a proper evaluation. Nevertheless, in the following years, the sagittal dimensions of the airway were the preferred parameters when analyzing the correlation between craniofacial morphology and nasorespiratory function (3–7) as well as when assessing the pathogenesis and treatment of obstructive sleep apnea (8–13).

Lateral cephalograms suffer from severe limitations with the inherent errors of a 2D representation of a 3-dimensional (3D) structure being distortion, differences in magnifications, superimposition of the bilateral craniofacial structures, and in addition, a low reproducibility as a result of difficulties in landmark identification (14–16). Another important drawback of lateral and frontal cephalograms is the lack of information about cross-sectional area and volume. Although it is understood that the use of lateral cephalogram still plays an important role in early diagnosis of nasopharyngeal obstructions (13, 17), the validity of this diagnostic approach to examine the anatomical features for the resistance to nasal breathing is questionable (18).

Computed tomography (CT) and magnetic resonance imaging (MRI) are able to depict the true 3D-morphology of the airway; however, their use is limited by high irradiation, cost, and restricted accessibility (19). Cone Beam CT (CBCT) with its low effective radiation dose represents an alternative technique to CT scanning for a comprehensive head and neck evaluation (20, 21). Despite the fact that with CBCT, it is not possible to discriminate between the various soft-tissue structures; nevertheless, it is possible to determine the boundaries between soft tissues and void spaces (i.e. air) making CBCT a potential diagnostic method to analyze and solve the problem related to 3D analysis of the airway.

Aboudara et al. (22) stated that CBCT is a simple and effective method to evaluate upper airway. They compared the volumetric measurements from CBCT with known physical airway phantoms and found that the errors ranged from 0 to 5%. They also reported a moderately high correlation ($r = 0.75$) between the sagittal area and the volume when correlating lateral cephalograms measurements with CBCT data.

CBCT raw data can be reformatted and exported using the Digital Imaging and Communications in Medicine (DICOM) format. CBCT data sets can, thus, be imported into various image-processing software where they can be further processed to synthesize various images, including 2D radiographic projections. Although 2D images synthesized from CBCT data sets have the disadvantage that much of the 3D information is lost, these images may be useful during the transition between 2D and 3D analyses while new methods of 3D evaluation are being developed (20). The validity of a 3D analysis depends on its reproducibility; therefore, a method for 3D evaluation of the upper airway has to be based on well-defined parameters.

The aim of this study was to assess the degree of correlation between assessments of the upper airway (from the top of the epiglottis until the adenoids) performed by means of linear measurements in the sagittal and the transversal plane of space, cross-sectional areas, and volumes.

Materials and methods

Subjects

Pre-treatment CBCT-scans of 34 patients (20 females, 14 males) were selected among the list of patients previously treated in the Postgraduate Clinic of the Orthodontic Department at the University of Aarhus, Denmark, with a mean age of 18 years ± 11 (min. 11, max. 56).

The inclusion criteria was that every patient had a 12″ CBCT-scan (NewTom 3G, QR s.r.l.; AFP Imaging, Elmsford, NY, USA) to have all the craniofacial structures required for the cephalometric analysis comprised in the CBCT data sets (Fig. 1). Moreover, the CBCT had to be taken with the patients in occlusion to reduce the inconsistency of mandibular position and soft-tissue airway measurements often associated with rest position (23). This study was approved by the Ethical Committee for Aarhus County, Denmark.

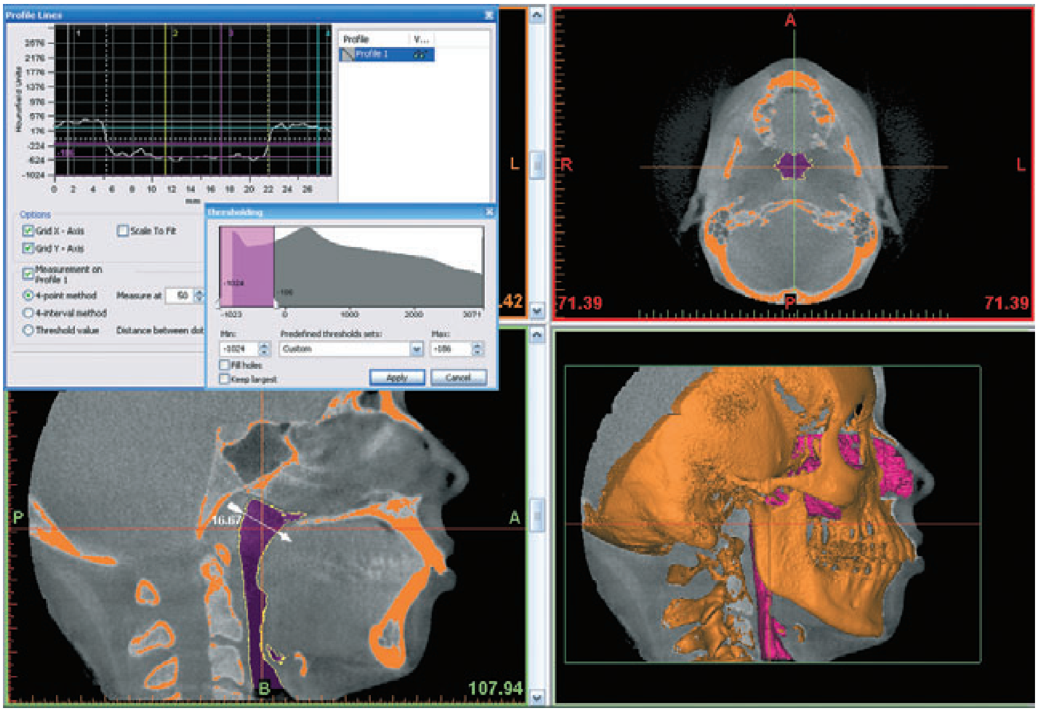

Fig. 1. Example of a 12″ CBCT-scan where the data set is presented both as stack of slices (sagittal, coronal, and axial) and as a 3D rendering. The various craniofacial structures are obtained by applying the appropriate threshold levels. This is performed by using the profile line drawn over the airway -gray line in the sagittal view (bottom, left) – and the correspondent vertical intersecting lines (top, left).

3D image processing

All CBCT-scans were reconstructed with an isotropic voxel dimension of 0.36 mm. Raw data obtained from CBCT-scanning were exported as DICOM format and imported into a specific software program (MIMICS 12.13 Materialise Interactive Medical Image Control System, Leuven, Belgium). Reconstructions of the coronal, sagittal, and transversal planes were analyzed. The threshold level was determined for each CBCT data set individually on the basis of a profile line and the correspondent vertical intersecting lines (Fig. 1). With the profile line it is possible to visualize a profile of the gray values or Hounsfield Units (HU), along a pre-defined line. Based on the minimal and maximal threshold values a layer of the relevant structures is defined (i.e., skeletal, soft tissues, and airways), and color-coded. This layer is called mask (Fig. 1). From the masks, the corresponding 3D surfaces were generated. The airway and craniofacial structures could be visualized in 3D (Fig. 1), sagittal and transversal linear measurements could be performed, and the cross-sectional areas and volume could be calculated. These parameters were used for 3D cephalometric airway analyses.

Determination of landmarks and cephalometric analysis

In MIMICS, a new template for a 3D cephalometric analysis reproducing the measurements usually performed on lateral cephalograms was generated. Using this template, nine conventional landmarks were identified for the cephalometric analysis, whereas for the upper airway analysis, 12 well-established antero-posterior landmarks were identified and six linear cephalometric measurements were performed based on them (24–29) (Tables 1 and 2; Figs 2 and 3). All landmarks were identified on the sagittal view of the midsagittal plane to better simulate what was normally performed on lateral cephalograms, and their position was checked on all the orthogonal planes, except for the bilateral points such as porion (Po), orbitale (Or), gonion (Go), and molar occlusion (mo), which were identified on the 3D surface and fine adjusted by checking and relocating them on the axial, coronal, and sagittal views (30).

Corresponding to the location of the above-mentioned linear measurements on the sagittal plane, six cross-sections of the airway were created, and the largest transversal linear dimensions and cross-sectional areas were computed. The total volume of the upper airway (TV), extending from the upper sagittal

Table 1. **Cephalometric landmarks**

Cephalometric points	
ad1	Intersection of the line PNS-Ba and the posterior nasopharyngeal wall
ad2	Intersection of the line PNS-So and the posterior nasopharyngeal wall
B	Most posterior point on the anterior contour of the lower alveolar process
Ba	Most postero-inferior point on the clivus
E	Most superior point of epiglottis
E1	Frontal wall of pharyngeal airway over E1-E2 line
E2	Posterior wall of pharyngeal airway over E1-E2 line
Go	Most posterior inferior point on the outline of the angle of the mandible
Mo	Middle of the first molars
Or	Deepest point on the infra-orbital margin
P	Most postero-inferior point of the soft palate
P′	Intersection between the PRL line and a perpendicular line passing through P
P3	Intersection between the posterior pharyngeal wall and the bisected Occlusal plane (OP)
Phw2	Posterior wall of pharyngeal airway on GoB line
ii	A point midway between the incisal edges of the maxillary and mandibular central incisors (bisecting the overbite)
PNS	The most posterior point on the bony hard palate
Po	Most superior point of the outline of the external auditory meatus.
S	Midpoint of the sella turcica
So	Midpoint of the sella-basion line
T2	Intersection between the contour of the tongue and the bisected OP
Tb	Dorsum of the tongue on GoB line

B, point B; Ba, basion; E, point E; Go, gonion; Mo, molar occlusion; Or, orbitale; PNS, posterior nasal spine; Po, porion; S, sella.

Table 2. **Cephalometric measurements**

Cephalometric measurements	
ad2-PNS	Upper sagittal depth of the nasopharyngeal airway
ad1-PNS	Lower sagittal depth of the nasopharyngeal airway
PNS-P	Soft palate length
T2-P3	Airway space measured from the dorsum of the tongue to the posterior pharyngeal wall on the bisected Occlusal plane (OP)
P-P′	Line from the most postero-inferior point of the soft palate to PRL line. (PRL = Line perpendicular to Frankfort horizontal plane passing through porion)
Phw2-Tb	Line from the posterior pharyngeal wall to the dorsum of the tongue on the GoB plane
E2-E1	Line passing through E, from posterior to the frontal wall of pharyngeal airway, perpendicular to PRL

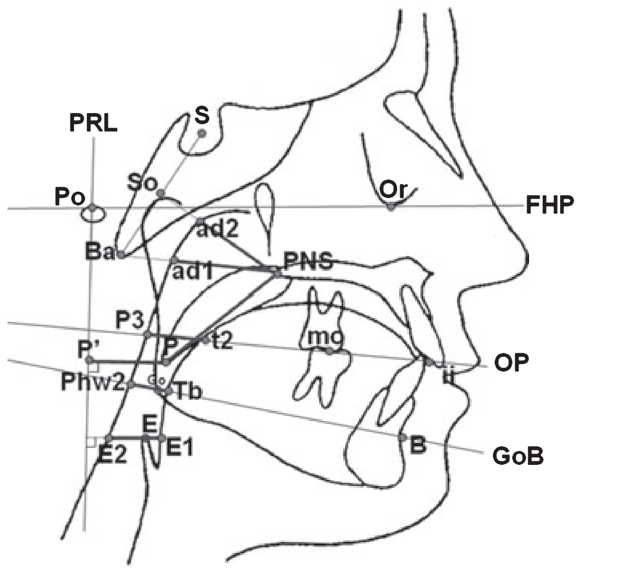

Fig. 2. Linear measurements used to describe the upper airway.

depth of the nasopharyngeal airway (ad2-PNS line) to the top of the epiglottis (E2-E1 line) and anteriorly delimited by the soft palate, the base of the tongue, and the anterior wall of the pharynx, was calculated. The upper airway was then divided into five parts (partial volumes), delimited by the previously defined six cross-sections (Table 3 and Fig. 4), and their volumes were calculated.

Anatomically, the structures were named describing the various portions of the pharyngeal airway, superiorly to inferiorly, as suggested by McCrillis (21).

Statistical analysis

The statistical analyses were carried out using SPSS (Version 13; SPSS, Chicago, IL, USA). All the measurements were performed by two of the authors (M.G.L. and M.M.O.L), who were trained and calibrated to identify 3D landmarks on axial, sagittal, and coronal planes. The intra-examiner error was calculated based on double

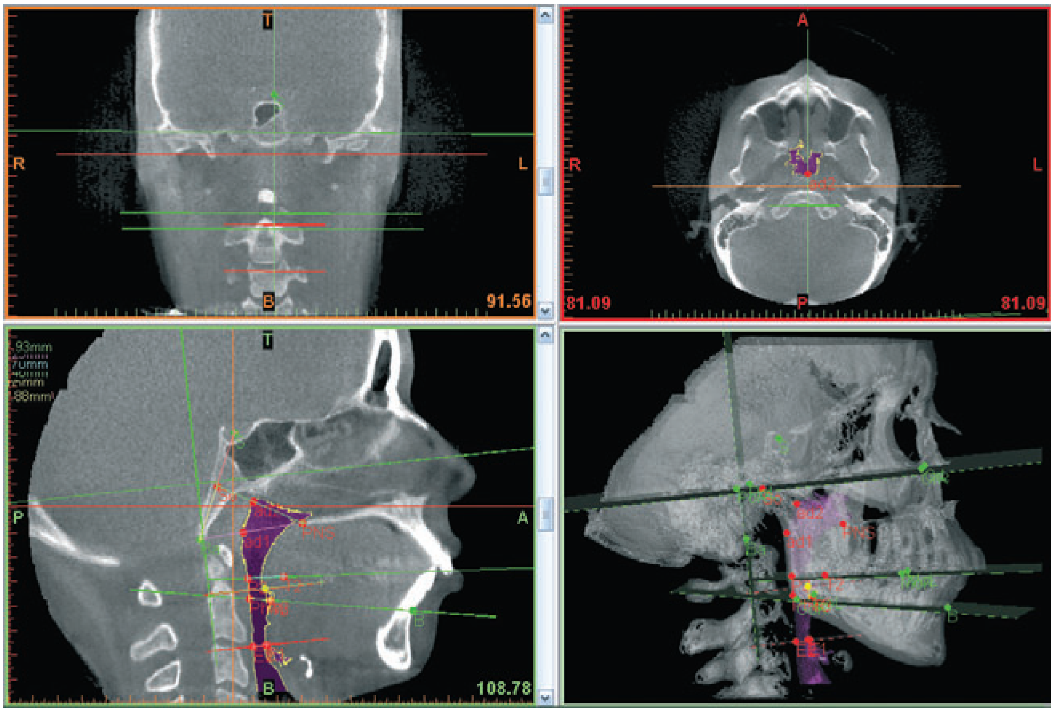

Fig. 3. Landmarks and planes used for the 3D cephalometric analysis.

Table 3. **Three-dimensional segments of the upper airway from which volume were calculated**

Three-dimensional airway	
TV	Bounded superiorly by ad2-PNS line and inferiorly by E1-E2 line
LNP	Bounded superiorly by ad2-PNS line and inferiorly by ad1-PNS line
UVLP	Bounded superiorly by ad1-PNS line and inferiorly by T2-P3 line
LVLP	Bounded superiorly by T2-P3 line and inferiorly by P-P' line
UORP	Bounded superiorly by P-P' line and inferiorly by Phw2-Tb line
LORP	Bounded superiorly by Phw2-Tb line and inferiorly by E1-E2 line

TV, total volume; LNP, lower nasopharynx; UVLP, upper velopharynx; LVLP, lower velopharynx; UORP, upper oropharynx; LORP, lower oropharynx.

measurements of five randomly selected cases at two different times using the Dahlberg's formula ($s = \sqrt{\sum d^2/2n}$). The analysis of variance (ANOVA) was applied to compare intra- and inter-examiner differences. The Student–Newman–Keuls *post hoc* test was used to determine which measurements were different.

Descriptive analysis including means, standard deviation, minimum, and maximum values of all measured and calculated variables was performed. All the data were checked to be normally distributed.

Correlation coefficients were assessed between the following: 1) Sagittal and transversal linear measurements; 2) Linear measurements (sagittal and transversal) and areas; 3) Average of two consecutive linear measurements (sagittal or transversal) and partial volumes; 4) Average of two consecutive areas and partial volumes; 5) Minimal sagittal, minimal transversal, and minimal area with the TV. The Pearson's correlation coefficient statistics was used to illustrate the correlation between the different measurements. When evaluating the correlation, the following classification was used: a *high* correlation when $r > 0.9$, *good* correlation if $0.8 < r < 0.9$, and *weak* correlation for $r < 0.8$.

Results

The calculation of the error of the method (Table 4) revealed that there were no significant statistical differences in the intra- and inter-observers measurements. Therefore, it was decided to pool the data and

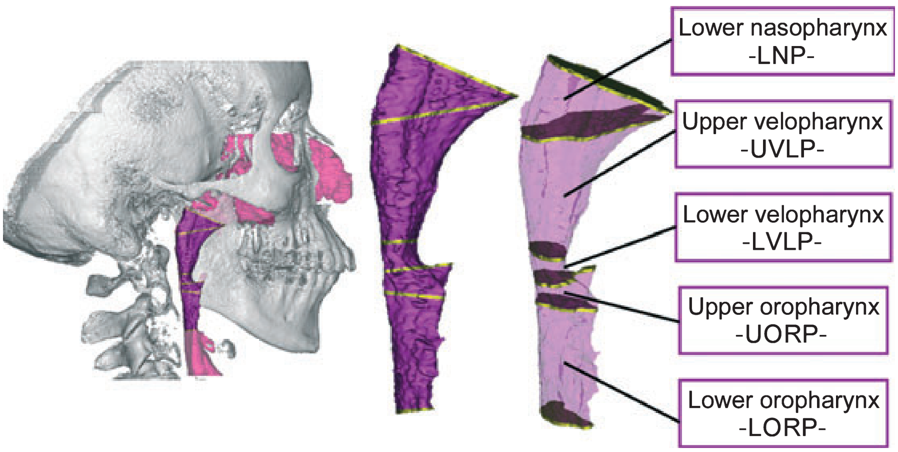

Fig. 4. Total airway and the five parts (partial volumes) delimited by the six cross-sections (depicted in yellow). Cross-sectional areas on inclined plane and on horizontal plane (right).

Table 4. **Descriptive analysis with means, standard deviation, minimum measurement, and maximum measurement**

	Level	Average	SD	Minimum	Maximum	Err. of Meth
Mimics Sagittal (mm)	ad2-PNS	16.05	4.86	6.29	27.36	0.95
	ad1-PNS	20.31	4.94	7.36	29.28	1.20
	T2-P3	16.09	2.97	10.76	23.58	0.83
	P'-P	24.39	5.00	12.18	33.72	1.20
	Phw2-Tb	11.28	2.82	4.77	18.18	0.42
	E2-E1	9.92	2.63	5.03	15.00	0.51
Transversal (mm)	ad2-PNS	24.33	2.58	16.35	29.08	0.93
	ad1-PNS	21.96	3.78	13.80	30.66	0.97
	T2-P3	16.67	4.79	6.76	28.86	1.08
	P'-P	15.95	5.23	6.69	32.90	1.26
	Phw2-Tb	18.67	5.52	10.94	37.91	1.35
	E2-E1	27.69	5.29	14.54	37.09	1.66
Area (mm^2)	ad2-PNS	264.97	111.62	83.97	593.52	19.08
	ad1-PNS	272.21	110.75	73.43	582.89	31.95
	T2-P3	84.43	35.19	25.43	201.02	10.40
	P′-P	117.57	59.11	44.00	334.87	19.07
	Phw2-Tb	157.74	54.96	73.18	297.90	14.34
	E2-E1	203.42	71.90	78.16	426.98	22.93
Volume (mm^3)	LNP	1780.86	987.36	300.38	4069.89	145.42
	UVLP	2898.39	1099.97	1071.64	6294.80	249.68
	LVLP	514.10	489.76	68.18	2938.77	168.32
	UORP	1101.67	731.31	122.35	3397.59	283.86
	LORP	2325.40	1240.17	204.03	5272.48	364.43
	TV	8620.41	2938.49	4092.33	16145.26	475.58

LNP, lower nasopharynx; UVLP, upper velopharynx; LVLP, lower velopharynx; UORP, upper oropharynx; LORP, lower oropharynx; TV, total volume.

use the averages of the measurements of the two examiners. The descriptive analyses showed that all parameters were characterized by a large inter-individual difference (Table 4).

Between sagittal and the transversal linear measurements, only a weak correlation was found (Table 5). The sagittal linear measurements were weakly correlated with all the area measurements,

Table 5. ***r* values for the correlations between sagittal and the transversal measurements; sagittal and its respective area, and transversal and its respective area**

Level	Correlation Sag. vs. trans. *r*	*p*-value	Correlation Sag. vs. area *r*	*p*-value	Correlation Trans. vs. area *r*	*p*-value
ad2-PNS	0.48	0.00	0.93	0.00	0.56	0.01
ad1-PNS	0.54	0.00	0.79	0.00	0.83	0.00
T2-P3	0.04	0.81	0.27	0.12	0.84	0.00
P'-P	–0.06	0.72	–0.02	0.91	0.81	0.00
Phw2-Tb	0.02	0.91	0.47	0.05	0.81	0.00
E2-E1	0.16	0.35	0.71	0.00	0.71	0.00

except the area at the level of ad2-PNS where a high correlation was found. The linear transversal measurements on the other hand expressed better the area measurements (or the cross-section): a good correlation was found for almost all of the sites, except for ad2-PNS and E2-E1 (Table 5). The correlation between sagittal linear measurements and partial volumes was weak for all the measurements, except for lower nasopharynx (LNP) where a high correlation was found. All the transversal linear measurements showed a weak correlation with its respective partial volume (Table 6).

When correlating area with partial volumes, a high correlation was found to LNP and a good correlation to upper velopharynx (UVLP). For the other three segments [lower velopharynx (LVLP), upper oropharynx (UORP) and lower oropharynx (LORP)], a weak correlation was found. A weak correlation was found between the minimal sagittal, minimal transversal, and minimal area with the TV of the upper airway (Table 7).

Table 6. ***r* values for the correlations between sagittal and the correspondent partial volume (P. volume); transversal and the correspondent partial volume, and between area and the correspondent partial volume**

Level	Correlation Sag. vs. P. volume *r*	Correlation Trans. vs. P. volume *r*	Correlation Area. vs. P. volume *r*
LNP	0.93	0.68	0.95
UVLP	0.37	0.63	0.80
LVLP	–0.10	0.50	0.63
UORP	0.11	0.73	0.71
LORP	0.27	0.46	0.51

LNP, lower nasopharynx; UVLP, upper velopharynx; LVLP, lower velopharynx; UORP, upper oropharynx; LORP, lower oropharynx.

Table 7. ***r* values for the correlations between the minimal sagittal measurement and the total volume (TV); minimal transversal measurement and total volume, and between minimal area and total volume**

Correlation Min. sag. vs. TV *r*	Correlation Min. trans. vs. TV *r*	Correlation Min. area vs. TV *r*
0.58	0.03	0.45

Discussion

In this study, the error of the method related to the description of the complex morphology of the upper airway was assessed. As both the intra- and the inter-observers variation related to all the variables was far below the standard deviation, the error in measuring could not be anticipated to influence the results.

In this study, a single threshold value was used to segment the airway in each patient's CBCT-scan. Given the characteristics of CBCT data sets, this approach might generate errors in the evaluation of the airways morphology, especially in respect to volume determination (22). However, this method was used as it was judged to be more reproducible than the use of dynamic threshold.

To evaluate how well the conventional measurements performed on lateral cephalograms represent the upper airway, linear, areas and volumes determined from a 3D CBCT data set were correlated.

With respect to the nasopharyngeal portion of the upper airway, only the 'ad2-PNS' was highly correlated with the area and to the volumetric expression of the airways in that region, This study thus corroborates the findings of Linder-Aronson and Leighton (24) who, in a retrospective study where lateral and frontal cephalograms as well as nasal airflow were analyzed, reported a positive correlation between clinical assessment and the measured dimensions of the adenoids and a negative correlation between nasal airflow and the measured adenoid size. They also reported a significant correlation between nasal airflow and the capacity of the nasal airway, and thus they concluded that lateral and frontal cephalograms provide satisfactory means of evaluating the dimensions of the nasopharynx and the capacity of the nasal airway. The correlation found in this study revealed that 86% of the variation in volume could be predicted from the sagittal linear measurement ($r^2 = 0.86$). These findings are strengthened by the fact that a high and good correlation was found between the cross-sectional areas at LNP and UVLP and the corresponding partial volumes. This is also in agreement with Aboudara et al. (22) who reported a significant positive relationship in adolescents between nasopharyngeal airway size measured on lateral headfilms and its true volume calculated from CBCT-scan.

For the lower part of the upper airway, only a weak correlation between all the parameters was found, and this is in agreement with Vig and Hall (18) who questioned the use of lateral cephalograms for assessing the overall morphology of the upper airway. The apparent controversy about the usefulness of cephalograms to evaluate the morphology of the entire upper airway can be better understood by carefully looking at its 3D actual structure. Indeed, the concerns of Vig and Hall can be explained by the fact that sagittal measurements on cephalograms cannot anticipate the morphology of upper airway, which is far from being cylindrical except for the nasopharynx part. The concern of these authors was shared by Hoffstein et al. (31). They demonstrated the limited usefulness of measurements of the airway obtained from routine lateral cephalograms as they could not distinguish between apneic- and non-apneic snorers based on measurement carried out on sagittal images. They concluded that, to have an accurate assessment of upper airway structure, more sophisticated imaging modalities, such as CT-scans or MRI were necessary. Montgomery et al. (32) were among the first to use CT to perform a 3D study of the nasal airway and they reported that this technique provides accurate cross-sectional area and volume measurement of the upper airway at any position. They also reported that the most constricted part of the airway is not necessarily located in the turbinates as claimed by Principato (33). Even though the adenoids may be important in some cases and the turbinates in others, information on the lower part of the upper airway may be crucial in some patients.

Airway volume might be variable regarding head posture and breathing stage (expiration or inhalation), as it is for lateral cephalograms. Although the upper airway is substantially affected by body posture (34, 35) Ingman et al. (36) suggested that a difference may occur on the oropharyngeal area, but not on naso- or hypopharyngeal area in supine position when compared with upright position.

Oral breathing and especially sleeping apnea are frequently but not always related to restricted airways. True information on the true anatomy of the airways is prerequisite for the correct treatment (37, 38). Medical CTs have been the method of choice to obtain 3D information of the upper airway. Although this method provide excellent evaluation of the airway, the advent of CBCT, with the advantage of lower costs and lower effective radiation dose for the patient then medical CT, has opened the opportunity to evaluate the cross-sectional area of the upper airway as well as the volumetric three-dimensional depiction of the entire upper airway with a rapid (20 s in average) non-invasive scan. Using CBCT-scans, Ogawa et al. (39, 40) measured the total airway volume, the smallest cross-sectional area, and anterior-posterior and transversal dimensions of the smallest cross-sectional area and demonstrated the utility of assessment of airway anatomy with 3D imaging. In agreement with this study, it was found that some important information about airway morphology cannot be detected on lateral cephalometric headfilms as opposite to CBCT-scans (41).

In this study, a good correlation was found between the transversal linear measurements and the area for almost all of the sites, except at the level of ad2-PNS and E2-E1, indicating that frontal cephalograms would be more valid in describing the lower portion of the upper airway. It is worth noticing that the cross-sectional areas were calculated on inclined planes corresponding to the sagittal measurement (Fig. 4) and not only along horizontal planes, as performed in other studies (39–42). This has a big impact especially when evaluating the most constricted area: measuring only on the horizontal plane would provide misleading results.

The importance of measuring the smallest airway lumen vs. the TV was emphasized by Haskell et al. (43), who claimed that, when treating obstructive sleep apnea patients, an improvement in a restrictive point in the airway might be just as or more important than the achievement of an overall volume increase. This was confirmed by this study: when the minimal sagittal, minimal transversal, and minimal area were correlated with the TV of the upper airway, a weak correlation was found. In other words, the TV of the upper airway fails to provide the relevant information about the more constricted cross-sectional area, which is the main factor in increasing the resistance to airflow (1). The most constricted area was found to be in the velopharynx, at the level of T2-P3 or P-P'. This is in agreement with the statements of Pillar and Lavie (44) (i.e. that the smallest airway luminal size generally is located at the level of the velopharynx, behind the soft palate).

Volume is only one of the assessments possible, and airway volume alone is particularly questionable because airways are extremely variable depending on head posture, breathing stage, and craniofacial morphology. Yet, some published studies report the volume as an important information in describing upper airway (21, 43, 45), or even as a risk factor of airway collapse and obstruction (46).

Conclusion

The morphology of the airways cannot be truthfully depicted with sagittal or transversal linear measurements independently. From the present results it was concluded that a 2D measurement neglects much of the information regarding the complex 3D structure of the upper airway. Moreover, volume alone does not depict the actual morphology of the airway. The best way to access the airway structure is a complete analysis with linear measurements, area and volume. Therefore, giving a 3D analysis, a full picture of the anatomical characteristics of the upper airway can help localizing the eventual obstacle to a normal breathing pattern and improve the diagnosis.

Clinical relevance

The correlation between the true airway anatomy determined on 3D CBCT images and the parameters used to express airways on lateral cephalograms was analyzed. The morphology of the upper airway cannot be truthfully depicted with sagittal or transversal linear measurements independently or with volume alone, as much of the information regarding the complex 3D structure of the upper airway is overlooked. These findings have a significant impact on the assessment of the pathogenesis and treatment of obstructive sleep apnea, localizing the eventual obstacle to a normal breathing pattern, or evaluating the relationship between craniofacial morphology and nasorespiratory function.

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