ORIGINAL ARTICLE

Eur. J. Anat. 21 (3): 197-209 (2017)

Development of the paranasal air sinuses in a South African Population utilising three dimensional (3D) reconstructed models

Carmen O. Rennie[1], Mohamed R. Haffajee[2], Kapil S. Satyapal[1]

[1]Department of Clinical Anatomy, School of Laboratory Medicine and Medical Sciences, College of Health Sciences, University of KwaZulu-Natal, Westville Campus, Durban, South Africa, [2]Ethekweni Hospital and Heart Centre, Durban, South Africa

SUMMARY

The anatomy of the paranasal air sinuses (PAS) may vary in form and size across populations, and between the sexes and age (Yun et al., 2011). This study aimed to estimate the volumes of the PAS within a South African population using the latest available radiological techniques. Computerized tomography scans (n=480) were reviewed from the Pietermaritzburg and Durban public and private sector hospitals (KwaZulu-Natal, South Africa). The sample consisted of 276 males, 204 females, with age range 1-25 yrs, representing the two main population groups (black African and white). The age range was divided into eight, three -year cohorts viz. 1-3; 4-6; 7-9; 10-12; 13-15; 16-18; 19-21; 22-25. These scans were processed by axial manual segmentation of the air sinuses using a 3D Slicer Program (http://www.slicer.org) to construct a three dimensional (3D) volume model of each PAS bilaterally, with 3840 3D models developed.

Maximum (max.) to minimum (min.) volumes for each PAS was as follows for ages: maxillary [max: 31563.3 mm^3(R), 32062.3 mm^3(L); min: 49.4 mm^3 (R), 25.4 mm^3(L)], frontal [max: 22908.6 mm^3(R), 21289.0 mm^3(L); min: 50.6 mm^3(R), 30.2 mm^3(L)], sphenoid [max: 15844.6 mm^3 (R), 15433.7 mm^3(L); min: 6.3 mm^3(R), 7.3 mm^3(L)] and ethmoid [max: 14327.5 mm^3(R), 13162.0 mm^3(L); min: 18.9 mm^3 (R), 12.6 mm^3(L)]. This demonstrated that the maxillary was the largest and the ethmoid the smallest PAS at full growth. At 1-3 years of age, the maxillary air sinus was the largest and the sphenoid air sinus was the smallest. Growth of the air sinuses correlated positively with age. Mean volumes appear to be larger on the left side at full growth, although not statistically significant. Sexual dimorphism was statistically significant for the right frontal sinus. Regarding population groups, notable volume differences were observed in the maxillary sinus bilaterally and left sphenoid sinuses unilaterally. There appeared to be four distinct periods in which the growth of the PAS changed. From ages 1 to 7 years there was a gradual increase with a peak increase from 7 to 9 years, continually increasing in growth rapidly, reaching a maximum by 16 to 18 years of age followed by a plateau thereafter.

This study presented data of the PAS of the South African populations using 3D reconstructed models. It is apparent that a study consisting of a large sample of 3D models of the PAS has not been fully reported. In particular, the volume of the ethmoid air sinus from 1 to 25 years of age was documented, which was not fully described. The study confirmed differences in terms of the paranasal air sinuses' size across populations, particularly the maxillary and sphenoid air sinuses, and sex

Corresponding author: Prof. Kapil S. Satyapal. Department of Clinical Anatomy, School of Laboratory Medicine and Medical Sciences, College of Health Sciences, University of KwaZulu-Natal, Private Bag X54001, Durban 4000, South Africa. Phone: + 27 31 260 7110 / + 27 83 777 8780; Fax: + 27 31 260 7890. E-mail: satyapalk@ukzn.ac.za

Submitted: 6 February, 2017. *Accepted:* 27 April, 2017.

differences viz. the right frontal air sinus.

Key words: Paranasal air sinuses – Volume – 3D reconstruction – Forensic anthropology

INTRODUCTION

The paranasal air sinuses (frontal, sphenoid, ethmoid and maxillary) are defined as air- filled pockets of bone surrounding the nasal cavity proper. They develop as diverticulae of the nasal cavity at the end of the third intrauterine month, maintaining communication with it via patent ostia (Marquez et al. 2014, cited by Chang et al., 2014). These outpouchings expand into the maxillary, sphenoid, frontal and ethmoid bones by growth of the mucous membrane sacs. This may be regarded as primary pneumatization (Scuderi et al., 1993). Enlargement of these outpouchings within the bones is described as secondary pneumatization, and this occurs at different rates post-natally (Wolf et al., 1993). The ethmoid and maxillary air sinuses are present at birth (Scuderi et al., 1993). In the case of the sphenoid and frontal air sinuses, pneumatization begins from 2 years onwards, once the red marrow contained in the sphenoid bone is converted to yellow marrow (Scuderi et al., 1993).

Various methods have been utilised in the literature to measure the volume of the PAS. In the latest studies, volume rendering techniques and three dimensional (3D) reconstruction models have been developed (Jun et al., 2005; Pirner et al., 2009; Kim et al., 2010; Park et al., 2010; Lee et al., 2012; Apuhan et al., 2011). Currently, CT imaging is the radiological technique of choice for analysing the PAS, as the distinction between bone, mucosa and other soft tissue can be clearly defined (Apuhan et al., 2011). According to Lee et al. (2012), 3D reconstructions from these CT images are able to yield a more precise form or 3D morphology of the PAS.

The literature reviewed reveals that the volume of the air sinuses is the most important parameter that can establish its size and these normal values may be useful in the diagnosis of sinus pathologies (Emirzeoglu et al., 2007; Adibelli et al., 2011), and in forensic identification of sex and ancestry (Fernandes, 2004). Therefore, evaluating volume and morphology in 3D of the PAS would theoretically be more accurate than closest estimates, offering values that are the best fit to their natural measurements (Apuhan et al., 2011). This first step of deriving norms of the volumes for the PAS in populations, followed by determining the actual morphological types or categories, would enable comparison with existing types in comparable populations according to age, sex and population.

Although there are studies from the early 1990s to the present that have estimated the volumes of the developing PAS, most of these studies have limitations [Table 1]. Some studies calculated the volume of the air sinuses by assuming the shape of the air sinus being ellipsoid, deriving an estimated volume, using the formula: $V=1/2 \cdot A \cdot B \cdot C$ (where A, B, C equal to ellipsoid diameters) from a few parameters (length, width and height) (Bargouth et al., 2002; Adibelli et al., 2011). This posed a problem as the air sinus shape and size are variable at different axial levels. Therefore, the estimated volumes overestimated the actual volume of the air sinuses by 4.7% (Adibelli et al., 2011). Studies by Sanchez Fernandez et al. (2000), Karakas et al. (2005), Emirzeoglu et al. (2007), Amusa et al. (2011), Apuhan et al. (2011) and Lee et al. (2012) reviewed a relatively small sample of CTs within this period [Table 1]. For example, the study by Karakas et al. (2005) analysed the volumes of the PAS in 91 scans of patients from 5 to 55 years of age. Some studies were not able to conclusively evaluate all the sinuses, for example, Spaeth et al.'s (1997) study consisting of 5600 CTs, was unable to comprehensively analyse the maxillary sinus, whilst, Karakas et al. (2005); Apuhan et al. (2011) and Lee et al. (2012) did not review the ethmoid air sinus development.

According to Shah et al. (2003) separating the age cohort is advantageous. However, some studies have analysed a few age categories that are too large, for example, Wolf et al.'s (1993) study divided their sample into four year age groups (1-4yrs; 4-8 yrs; 8-12yrs), Karakas et al. (2005) into five year age groups (1-5yrs; 6-10 yrs; 11-15yrs; 16-20 yrs) and Sanchez Fernandez et al. (2000) into two large age cohorts (≤20yrs and >20yrs). Further, the development of the PAS for these studies have been limited to a maximum of 12 years (Wolf et al., 1993), 16 to 18 years (Bargouth et al., 2002; Apuhan et al., 2011; Adibelli et al., 2011) or up to 25 years of age (Spaeth et al., 1997; Park et al., 2010). According to Adibelli et al. (2011) "normal paranasal air sinus development may continue into early adulthood". Furthermore, early adulthood according to anatomical textbooks is defined as 21 to 25 years of age, when all ossification and growth is complete (Moore et al., 2016). In addition, Park et al. (2010) further explain that few studies have illustrated the growth of the air sinuses for all age periods, particularly the growing period of 1 to 25 years.

Karakas et al. (2005) and Emirzeoglu et al. (2007) evaluated the volumes of the air sinuses in childhood, but, calculating the volumes using CTs with slice thicknesses of 3-5 mm. These estimates posed a problem, as the fronto-nasal complex is extremely difficult to analyse at that thickness, and the methods are not clearly elaborated on nor are they comprehensively shown. Most of the studies (Kim et al., 2010; Park et al., 2010; Apuhan et al., 2011) were conducted in Asian population groups, making generalisations difficult.

In Southern Africa there is a paucity of studies on the mean volumes of the air sinuses, illustrating the development of the air sinuses particularly in the study period. Furthermore, those studies that were conducted derived measurements from dried cadaveric skulls of adults only (Wolfowitz, 1974; Fernandes, 2004; Amusa et al., 2011). According to StatsSA statistical release 2016 (www.statssa.gov.za), the South African population is stratified into four distinct populations: viz. black African, coloured, Indian/Asian and white population groups. There is significant literature on the growth of the PAS in populations of European descent, and therefore in the current study, the growth of the PAS in the white population group was compared with the largest population group within South Africa, viz. the black African population.

An extensive literature review revealed that there is little knowledge on the morphometry, morphology and the growth of the PAS within a South African population. Therefore, this study aimed to derive norms for the development of the PAS from ages 1 to 25 years, with a view to elaborating on the developing volume morphometry of the PAS and its relationship to age, sex, laterality and in a South African population.

MATERIALS AND METHODS

This study was a retrospective review and analysis of computerized tomography (CT) scans of patients attending the radiology departments in both public and private hospitals in Pietermaritzburg and Durban, KwaZulu-Natal (KZN), South Africa, over a period of five years (2011-2016). Ethical clearance was obtained from the University of KwaZulu-Natal Biomedical Research Ethics Committee (BE247/11) and the Department of Health, KZN.

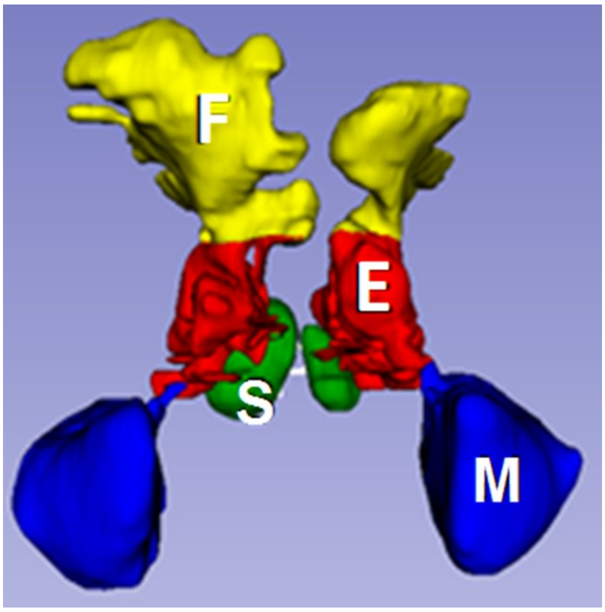
Table 1. Previous studies analyzing the volume of the paranasal air sinuses.

Author	Sample Size (n)	Age (yrs)	Population	Methodology	Mean Volumes (cm^3)			
					Maxillary	Frontal	Sphenoid	Ethmoid
Sanchez Fernandez 2000	100 normal controls & 163 patients	1-88	Spanish	Axial, coronal CT images, calculated volume, trapezoidal rule	(9.9 R; 9.9 L) M (7.9 R; 8.8 L) F	(1.9 R; 1.9L) M (1.6 R; 2.1 L) F	(2.2 R; 2.4 L) M (3.6 R; 3.3 L) F	(4.0 R; 3.9 L) M (3.3 R; 3.4 L) F
Bargouth 2002	179	1-17	Swedish	MRI, sinus volume index calculated	18.3 (16 years)		2.7 (16 years)	-
Karakas 2005	91	5 – 55	Turkish	CT scans, calculated volume based on Cavalieri principle	(15.0 R; 16.0 L) M (11.1 R; 11.5 L) F (>25 years)	8.4 M 3.5 F (>25 years)	8.5 M 7.9 F (>25 years)	-
Emirzeoglu 2007	77	18 – 72	Turkish	CT scans, calculated volume, stereological method, Cavalieri principle	19.8 (M) 16.0 (F) 35.9 (B)	7.5 M 4.1 F 11.6 B	7.7 (M) 6.1 (F) 13.6 (B)	6.3 (M) 5.5 (F) 11.8 (B)
Pirner 2009	50	16 – 78	German	Spiral CT scans, manual segmentation	17.4 (R) 17.9 (L)	4.2 R 4.0 L	5.3 R 5.5 L	-
Park 2010	260	0-25	Asian	CT scans, 3D reconstruction	14.8	3.5	3.5	4.5
Kim 2010	60	18 – 63	Korean	CT scans, 3D reconstruction	41.6	6.8	13.8	-
Adibelli 2011	1452	0-18	Turkish	MRI, sinus volume index	23.7 (15 -18 yrs)	6.3 (15 -18 yrs)	4.96 (15 -18 yrs)	4.6 (15 -18 yrs)
Amusa 2011	24	Adult	Nigerian	Endoscopy, vernier calipers, volume water displacement	26.6	7.8	9.6	9.9
Apuhan 2011	104	3-16	Turkish	Multislice CT, 3D reconstruction	24.5	4.6	7.4	-
Lee 2012	62	<18 years	Korean	Multislice CT, 3D reconstruction	8.6 (R) 8.8 (L)	3.6 (R) 3.9 (L)	3.2 (R) 3.3 (L)	3.5 (R) 3.4 (L)

Key: R-right, L-left, B-bilateral, M-males, F-females

CT images of approximately 7000 patients were reviewed from the picture archiving and communication system (PACS) of the state hospital (Greys Hospital) and the archives of radiologists Jackpersad and Partners, Specialist Diagnostic Radiologists (Ethekweni Hospital and Heart Centre and Isipingo Hospital).

The inclusion criteria were the following: a) patients between 1-25 years of age; b) images without observable signs of abnormal pathological processes of the paranasal air sinuses; c) slice thickness <1.25mm d) non-distorted images, and e) the largest population groups attending the state and private hospitals above.



A final suitable sample, that satisfied the inclusion criteria, of n=480 patients was obtained. These consisted of 276 males and 204 females, all between the ages of 1-25 years old and of two population groups (black African and white). Growth of the air sinuses was compared with age, sex and ancestry. The age period was limited to 25 years as stipulated in similar studies by Spaeth et al. (1997) and Park et al. (2010). Furthermore, the age range of 1-25 years was conveniently subdivided into eight, three-year cohorts viz. 1-3; 4-6; 7-9; 10-12; 13-15; 16-18; 19-21; 22-25 in order to reasonably capture and compare the growth of the air sinuses. Age categorization in this study simulated that reported by Adibelli et al. (2011).

The DICOM images of the patients were then transferred and viewed on a personal computer (HP Probook 450, 64bit, Intel core i3, 4GB RAM). The images of each patient were of slice thicknesses between 0.625 to 1.25mm in the axial plane, and were imported to SLICER 3D (www.slicer.org). SLICER 3D also allowed for viewing of the DICOM images in the three different planes viz. axial, sagittal and coronal (Fig. 1).

The axial view was selected as the most convenient and easiest method to trace axial contours of the sinuses for further analysis. Once each sinus was manually segmentally traced (per slice) from the floor to roof, the 3D models of each paranasal air sinus was reconstructed. Beginning at the cranial end of the skull, the area of interest was selected, using minimum and maximum threshold values in Hounsfield units (-1024 to -318). By using the Model module, the 3D model was then re-

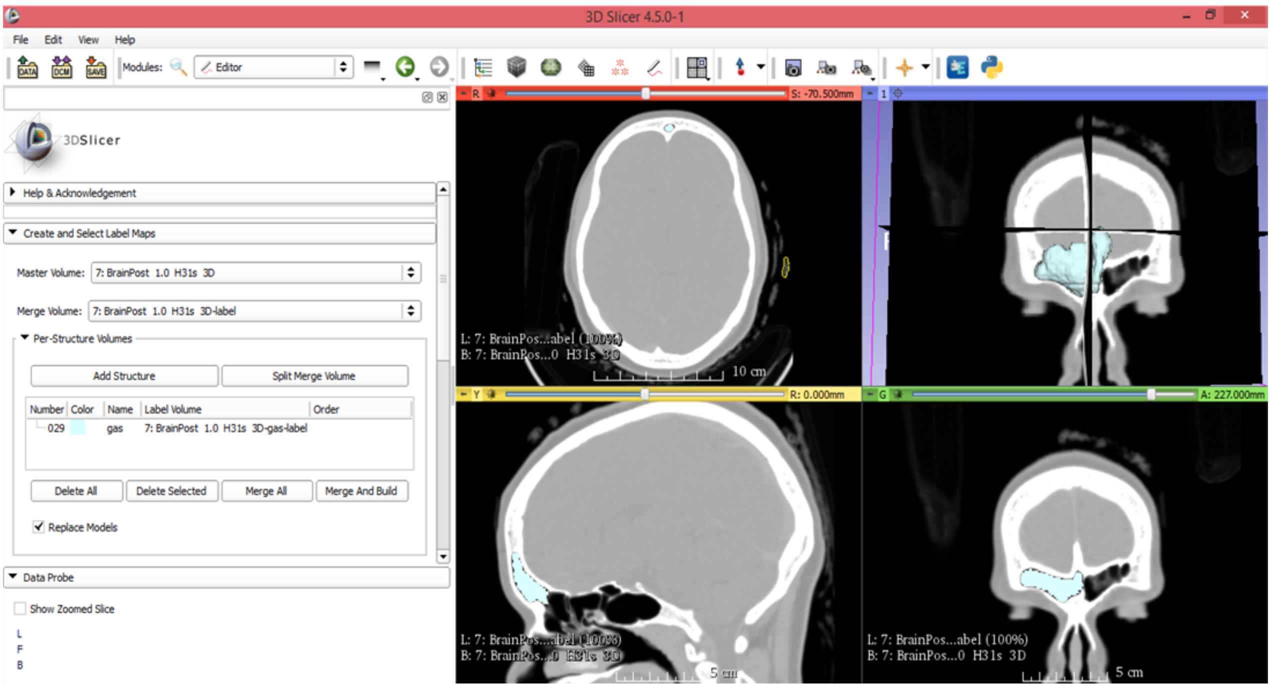


Fig 1. Three dimensional reconstruction process and 3D models using Slicer 3D. E -Ethmoid air sinus, S-Sphenoid air sinus, F-Frontal air sinus, M- Maxillary air sinus.

constructed and the named model saved as a VTK file. SLICER 3D then calculated the bilateral volumes (right and left sides) of each PAS from these 3D models. Volumes of the PAS were determined and measured in mm³ according to the SLICER 3D program (Fig. 1).

Statistical Analysis

The Statistical Package for social sciences SPSS version 24.0 (IBM® SPSS Inc., Chicago, Illinois, USA) was used to analyse the data. A P-value less than 0.05 was considered statistically significant. The bilateral volumes of the air sinuses were compared according to the age, sex, laterality and population groups. The ANOVA test was used to compare the means of the PAS volumes between the age groups. Furthermore, the Tukey's Posthoc test was used to indicate which age groups were statistically different in terms of the PAS volumes. The independent t test was used to determine a significant difference, if any, between the volumes of the PAS with regard to sex, ancestry and laterality. Lastly, the Pearson's correlation test was applied to evaluate whether a relationship existed between all four air sinuses according to age, and, in addition, the strength and the direction of this relationship was determined.

RESULTS

Computerized tomography (CT) scans of 480 patients (276 males, 204 females; 433 black African, 47 white) were reviewed. The sample consisted of patients between 1-25 years (mean age of 14.5 years). The bilateral volumes of all four PAS were obtained from a total of n=3840 3D reconstructed models. A study consisting of a large sample of 3D models of the PAS has not been previously documented. The findings highlighted the development of all the air sinuses according to age utilising 3D reconstruction. In particular, the volume of the ethmoid air sinus from 1 to 25 years of age was documented, which was not done previously.

Laterality

The means and standard deviations of the volumes of each paranasal air sinus were determined and are indicated in Table 2.

The data revealed that the maximum volumes reached were as follows: maxillary air sinus [31563. 3 mm^3(R); 32062. 3 mm^3 (L)], frontal air sinus [22908. 6 mm^3 (R); 21289. 0 mm^3 (L)]; sphenoid air sinus [15844.6 mm^3 (R); 15433.7 mm^3 (L)]

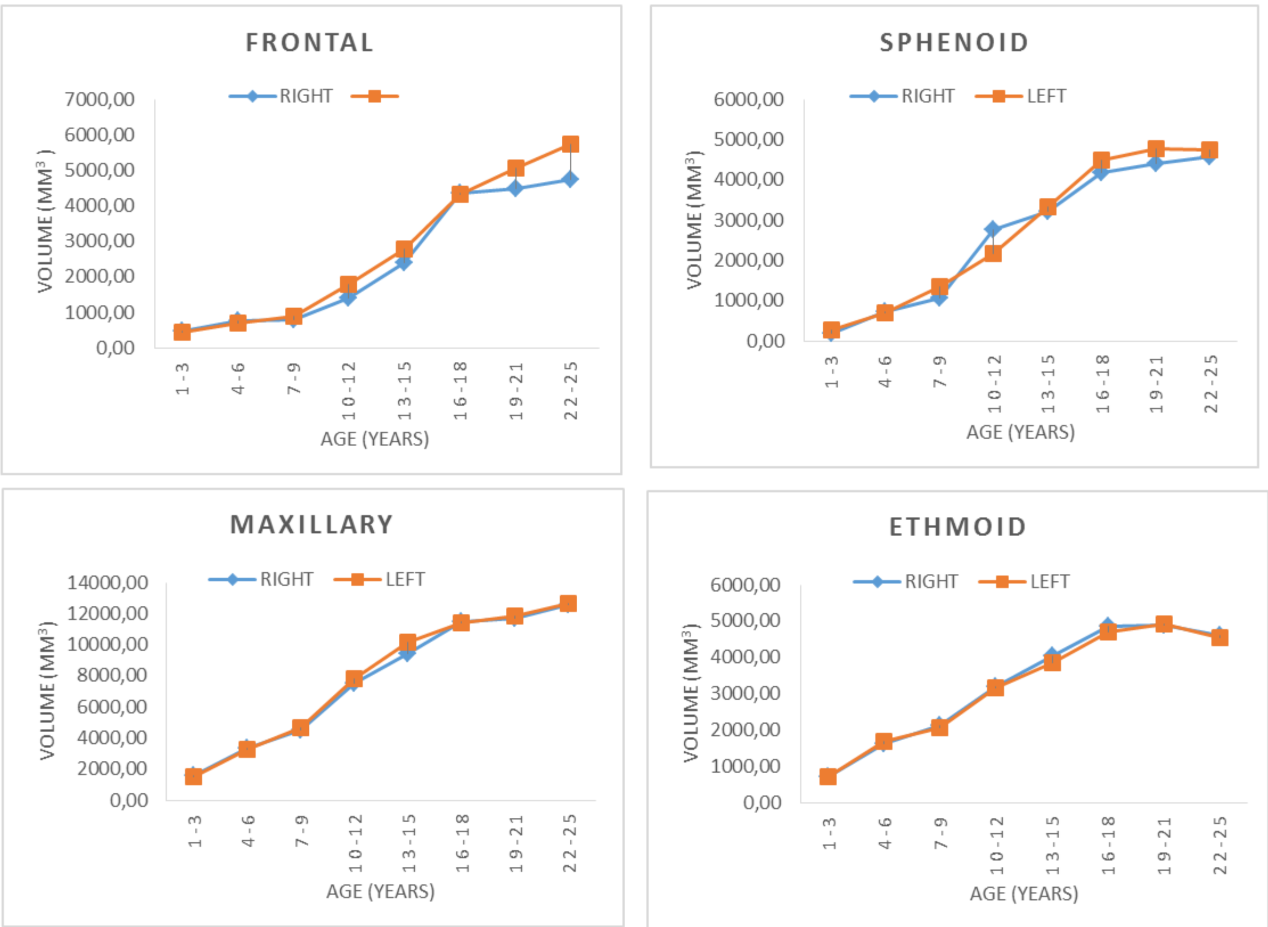


Fig 2a-d. Comparison of the growth of the paranasal air sinuses according to laterality and ethmoid air sinus [14327.5 mm^3(R); 13 162.0 mm^3 (L)]. This illustrated that overall the largest volumes were for the maxillary air sinus with smallest volumes for the ethmoid air sinus.

The minimum values were as follows: the frontal air sinus [50. 6 mm^3 (R); 30. 2 mm^3 (L)]; maxillary

Fig 3 a-h. Comparison of the growth of the paranasal air sinuses according to sex.

air sinus [49. 4 mm^3 (R); 25.4 mm^3 (L)]; ethmoid air sinus [18.9 mm^3 (R); 12.6 mm^3 (L)] and sphenoid air sinus [6.3 mm^3 (R); 7.3mm^3 (L)]. Although these values were not statistically significant in terms of laterality, they indicated that at full growth, the volumes appear to be larger on the left side, whilst at birth the volumes of the air sinuses were larger on the right side.

The mean volumes of the right and left air sinuses were as follows: maxillary air sinus [8727. 3 mm^3 (R); 8849.5 mm^3 (L)]; frontal air sinus [(3605.0 mm^3 (R); 4029.9 mm^3 (L)]; ethmoid air sinus [3558.2 mm^3 (R); 3512.7 mm^3 (L)] and sphenoid air sinus [3243.7 mm^3 (R); 3396.0 mm^3 (L)]. Analysis of the mean volumes within the different age categories illustrated that the growth of the right and left air sinuses was symmetrical (p>0.05) as well, with no significant difference between male and female air sinuses. Variation of the growth of the air sinuses was notable with regards to the population groups, particularly in the maxillary air sinuses and left sphenoid air sinus, which was larger within the white South African population.

Age

The Pearson correlation test revealed that all the air sinuses correlated positively with age and this relationship was statistically significant (p <0.05) (Table 2). There was a good correlation between each of the air sinuses' growth, suggesting that they grow in proportion with each other (Table 2). The maxillary and ethmoid air sinuses had the strongest correlation with age (r >0.5). The graphs of the volumes of the paranasal air sinuses were plotted against age, confirming that the air sinuses' growth correlated positively with age and that the right and left sides were symmetrical (Fig. 2a-d), except for the frontal air sinuses, illustrating apparently different growth patterns after 16-18 years.

The appearance of the air sinus in the CT scan for the first time is listed in Table 3 in percentages. The data revealed that all air sinuses were present between 1 to 3 years of age. However, the sample revealed that the ethmoid and maxillary air sinuses were the first to appear, at 1 to 3 years of age (>95% bilaterally). They were present in 100% of the sample by the ages of 4 to 6 years. The frontal air sinuses appeared at 1 to 3 years of age in only 10.3 % on the right and 13.2% on the left, reaching 50% by ages 4 to 6 years, and finally 100% by ages 16 to 18 years. The sphenoid air sinuses were present bilaterally by the ages 1 to 3 years in approximately 55.9% on the right and 54.4% on the left side, appearing in 100% of the sample by ages 13 to 15 years.

The full age range was subdivided into eight three year categories viz. 1-3; 4-6; 7-9; 10-12; 13-15; 16-18; 19-21; 22-25. The volumes according to these age categories are listed in Table 4. The table indicated that the maximum volumes reached of the paranasal air sinuses was observed during 22 to 25 years of age for the frontal [22908.6 mm^3 (R); 21289.0 mm^3 (L)] and sphenoid air sinuses [15844.6 mm^3(R); 15433.7mm^3 (L)], whilst the maximum volumes reached for the ethmoid [14327.5 mm^3(R); 13162.0 mm^3 (L)] and maxillary air sinuses [31563.3 mm^3(R); 32062.3 mm^3 (L)] was during 19 to 21 years of age. The minimum values of the air sinuses overall was observed between 1 to 3 years of age (Table 4).

The growth rates of the PAS increased throughout the period considered, but the ANOVA test revealed that the sinuses increased and varied with age and was statistically different within the age groups (p<0.001). This test together with the growth curves (Fig. 2a-d) illustrated the growth patterns of each air sinus. There appeared to be four distinct periods in which the growth rates changed. From ages 1 to 7 years there is a gradual increase with a peak increase from 7 to 9 years, continually increasing in growth rapidly, reaching a maximum by 16 to 18 years of age followed by a plateau thereafter.

It was also evident that the growth rates of the two sides were symmetrical except for the frontal and sphenoid air sinuses. The frontal air sinus volume on the left side seems to expand further after the period of 16 to 18 years of age, with no change in growth on the right side after this period. In the

Table 2. Minimum, maximum and mean volumes of the paranasal air sinuses and relationship with age (mm^3).

	Frontal		Sphenoid		Maxillary		Ethmoid	
	RIGHT	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	LEFT
N	364	372	442	441	477	477	479	478
Minimum	50.6	30.2	6.3	7.34	49.4	25.4	18.9	12.6
Maximum	22908.6	21289.0	15844.6	15433.7	31563.3	32062.3	14327.5	13162.0
Mean	3605.0	4029.9	3243.7	3396.0	8727.3	8849.5	3558.2	3512.7
p-value	**0.11**		**0.45**		**0.76**		**0.74**	
Std Deviation	3469.5	3671.1	3048.0	2992.2	6046.5	6198.4	2140.7	2094.7
Pearson Correlation	0.40*	0.48*	0.512*	0.55*	0.67*	0.66*	0.69*	0.70*
Sig. (2 tailed)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

sphenoid air sinuses, the right air sinus appears to grow at a faster rate than the left side in the cohort 10 to 12 years of age. The maximum volumes were not apparently reached by the left frontal and maxillary air sinuses bilaterally according to these graphs. It is possible that the growth rate curve

Fig 4 a-h. Comparison of the growth of the paranasal air sinuses according to population groups continued beyond 25 years of age. The ethmoid and sphenoid air sinuses, on the other hand seem to plateau, indicating no change in growth beyond 18 years of age.

Sex

Comparison of male and female mean volumes according to sex using the independent samples t-test are shown in Table 5 and illustrated in Fig. 3a-h. The data indicated that the mean volumes for the air sinuses were larger in males, although not statistically significant. However, the right frontal air sinus was significantly larger in males. The growth charts illustrated that the male and female air sinuses have similar growth patterns which are in synchrony with the overall development of the air sinuses within this period from ages 1 to 18 years. However, after this period, the female volumes seem to be smaller.

NB. Graphically it appears that sex differences manifest more in the older age groups i.e. male and female graphs diverge in Fig. 3 a-h.

Population groups

The independent samples t-test compared the mean volume of each paranasal air sinus in relation to the two population groups within the sample, and revealed that variations in terms of the air sinuses size exist and this may be attributed to differences within the population groups (Table 6) (Fig. 4 a-h). This variation was found to be statistically significant ($p<0.001$) bilaterally for the maxillary air sinus and the left sphenoid air sinus only (Table 6). These mean volumes were greater in the South African white population. There were no statistically significant differences observed in the remaining air sinuses.

DISCUSSION

Although the anatomy of the PAS has been assessed using cadaveric specimens, plain radiographs and magnetic resonance imaging, the literature suggests that these studies have their limitations (Jun et al., 2005) and that CT imaging is the optimal technique in defining the PAS anatomy (Apuhan et al., 2011). Advances in radiology have improved the definition of the PAS anatomy. Utilisation of such advanced radiographical imaging techniques e.g. CT imaging with 3D reconstruction, as conducted in this study, should ensure accurate data capture of both the morphology and morphometry of the PAS. In addition, CT costs less than MRI and provides a perfect evaluation of the sinonasal area (Apuhan et al., 2011). According to the literature reviewed, the volumes of the PAS are the simplest, most comprehensive means to appreciate the extent and anatomy of these air filled spaces (Apuhan et al., 2011). The current study was undertaken to provide normal volumetric

Table 3. Appearance of the paranasal air sinus according to age.

			RIGHT		LEFT					RIGHT		LEFT	
	AGE (yrs)	n	incidence	%	incidence	%		AGE (yrs)	N	incidence	%	incidence	%
Frontal	1-3	68	7	10.3	9	13.2	Sphenoid	1-3	68	38	55.9	37	54.4
	4-6	44	19	43.2	22	50.0		4-6	44	41	93.2	39	88.6
	7-9	30	14	46.7	18	60.0		7-9	30	29	96.67	29	96.7
	10-12	41	35	85.4	34	82.9		10-12	41	38	92.7	40	97.6
	13-15	43	40	93.0	40	93.0		13-15	43	43	100.0	43	100.0
	16-18	57	57	100.0	57	100.0		16-18	57	56	98.3	56	98.3
	19-21	89	86	96.6	86	96.6		19-21	89	89	100.0	89	100.0
	22-25	108	106	98.2	106	98.2		22-25	108	108	100.0	108	100.0
	Total	480	364	75.8	372	77.5		Total	480	442	92.1	441	91.9
Maxillary	1-3	68	65	95.6	65	95.6	Ethmoid	1-3	68	67	98.5	66	97.1
	4-6	44	44	100.0	44	100.0		4-6	44	44	100.0	44	100.0
	7-9	30	30	100.0	30	100.0		7-9	30	30	100.0	30	100.0
	10-12	41	41	100.0	41	100.0		10-12	41	41	100.0	41	100.0
	13-15	43	43	100.0	43	100.0		13-15	43	43	100.0	43	100.0
	16-18	57	57	100.0	57	100.0		16-18	57	57	100.0	57	100.0
	19-21	89	89	100.0	89	100.0		19-21	89	89	100.0	89	100.0
	22-25	108	108	100.0	108	100.0		22-25	108	108	100.0	108	100.0
	Total	480	477	99.4	477	99.4		Total	480	479	99.8	478	99.6

Table 4. Volumes of the paranasal air sinuses according to age cohorts (mm^3).

AIR SINUS		FRONTAL		SPHENOID	
AGE (YRS)		RIGHT	LEFT	RIGHT	LEFT
1-3 p=0.000	Mean ± std	485.7 ± 539.5	438.2 ± 779.6	196.6 ± 277.7	272.9 ± 390.5
	Range	65.1 - 1549.0	30.2 – 2478.2	6.3 -1325.5	7.3 – 1719.2
	N	7	9	38	37
4-6 p=0.000	Mean ± std	763.1 ± 977.8	701.4 ± 942.3	723.7 ± 680.3	699.1 ± 607.2
	Range	63.5 – 3827.0	135.7 to 4307.7	42.4 -3075.3	30.3 -2726.1
	N	19	22	41	39
7-9 p=0.000	Mean ± std	808.1 ± 768.9	885.2 ± 733.6	1068.4 ± 1223.9	1358.6 ± 1550.3
	Range	96.5 -3049.2	69.5 – 2532.3	55.5 – 5445.0	34.7-5316.5
	N	14	18	29	29
10-12 p=0.000	Mean ± std	1418.5 ± 1410.2	1796.4 ± 1648.4	2767.4 ± 2034.6	2183.7 ± 1580.0
	Range	210.4 – 6047.7	162.1- 6043.2	165.2 – 8148.9	44.9 – 5369.0
	N	35	34	38	40
13-15 p=0.000	Mean ± std	2396.8 ± 1804.4	2793.6 ± 2315.3	3217.2 ± 2713.7	3339.2 ± 2220.8
	Range	50.6 – 7574.0	337.7 – 9399.5	84.1 -12838.6	72.8 – 8581.2
	N	40	40	43	43
16-18 p=0.000	Mean ± std	4348.0 ± 2985.0	4327.3 ± 3029.9	4187.6 ± 2753.6	4503.3 ± 2735.5
	Range	466.4 – 13221.8	239.2 – 13593.2	310.1 -13448.3	408.1- 11219.3
	N	57	57	56	56
19-21 p=0.000	Mean ± std	4475.5 ± 3695.1	5065.7 ± 3470.5	4408.9 ± 3146.7	4789.4 ± 3115.9
	Range	206.3 – 20520.7	265.0 – 17814.8	263.2 -12053.8	257.5-15192.0
	N	86	86	89	89
22-25 p=0.000	Mean ± std	4762.0±4016.2	4313.9	4584.9±3291.1	4735.9±3092.1
	Range	116.1 – 22908.6	102.5 -21289.0	169.3 -15844.6	395.3-15433.7
	N	106	106	108	108

AIR SINUS		MAXILLARY		ETHMOID	
AGE (YRS)		RIGHT	LEFT	RIGHT	LEFT
1-3 p=0.000	Mean ± std	1616.2 ± 1306.7	1567.7 ± 1247.5	736.7 ± 473.5	716.9 ± 536.9
	Range	49.4-5882.4	25.4-5810.7	18.9-1933.9	12.6 -2100.4
	N	65	65	67	66
4-6 p=0.000	Mean ± std	3338.4 ± 1541.6	3326.5 ± 1524.5	1639.4 ± 790.7	1709.4 ± 851.8
	Range	681.6 -6264.2	443.1 – 6804.4	322.5-3710.2	585.2-4355.4
	N	44	44	44	44
7-9 p=0.000	Mean ± std	4556.4 ± 2411.1	4683.5 ± 2557.4	2127,0 ± 1088,3	2060.6 ± 927.6
	Range	418.3-11809.4	590.0 -11585.4	114.9-4688.4	338.5-4740.0
	N	30	30	30	30
10-12 p=0.000	Mean ± std	7528.9 ± 3066.6	7824.5 ± 2928.6	3210.6 ± 1222.1	3163.1±1259.3
	Range	2162.6 -13829.5	2424.7-14653.5	339.9 -6046.9	408.2-6272.2
	N	41	41	41	41
13-15 p=0.000	Mean ± std	9470.7 ± 4494.8	10201.6 ± 4770.5	4055.8 ± 1561.9	3846.7±1326.3
	Range	2524.8 -20202.8	1904.2 – 21183.7	1120.7-8438.2	1349.0-7064.1
	N	43	43	43	43
16-18 p=0.000	Mean ± std	11475.6 ± 4677.8	11425.2 ± 5405.7	4862.6 ± 1672.3	4706.3±1690.3
	Range	2074.0 -20515.1	1245.8 -23945.4	2023.4-8000.9	1687.3-8716.1
	N	57	57	57	57
19-21 p=0.000	Mean ± std	11748 ± 6240.5	11871.1 ± 6281.9	4904.2 ± 1915.3	4934.5±1963.5
	Range	2362.8-31563.3	2044.3 – 32062.3	1347.2-14327.5	1809.4-13162.0
	N	89	89	89	89
22-25 p=0.000	Mean ± std	12580.0 ± 5408.8	12640.7 ±5567.7	4624.10±1727.8	4557.6±1589.7
	Range	2266.0 -25600.3	1881.7 – 30088.7	1218.6-10360.9	559.5-10736.9
	N	108	108	108	108

parameters for a South African population for the period of development of the sinuses from 1 to 25 years. It is apparent that a detailed study of this nature and depth has not been previously reported. The volume of the PAS should be a first step in understanding the air sinus size and form within a population, in order to compare pneumatization patterns between population and age groups.

Various methods have been explored to estimate the volumes of the PAS, with few studies having explored the entire developmental change from childhood to young adulthood. Previous volumetric studies are reflected in Table 1. Furthermore, these studies show the necessity for specific population data (Amusa et al., 2011). The current study illustrated that the mean volumes of the right and left air sinuses were symmetrical (p>0.05) and were as follows: maxillary air sinus [8727.3 mm^3 (R); 8849.5 mm^3 (L)]; frontal air sinus [3605.0 mm^3 (R); 4029.9 mm^3 (L)]; ethmoid air sinus [3558.2 mm^3 (R); 3512.7 mm^3 (L)] and sphenoid air sinus [3243.7 mm^3 (R); 3396.0 mm^3 (L)]. The current study confirmed the findings of Wolfowitz (1978), in that the mean bilateral volume for the maxillary air sinus was the largest and the sphenoid air sinus was the smallest.

Age and the paranasal air sinuses

The data from this study revealed that all the air sinuses are present between the ages of 1-3 years. The ethmoid and maxillary air sinuses are the first to appear, in 100% of the sample by the ages 4 to 6 years. The frontal air sinuses appeared in 100% by the ages 16 to 18 years, whilst, the sphenoid air sinuses were present bilaterally in 100% of the sample by ages 13 to 15 years. This confirmed studies by Scuderi et al. (1993) and Spaeth et al. (1997), in that the maxillary and ethmoid air sinus are the first to appear at birth, followed by the sphenoid and frontal air sinuses.

According to standard anatomical textbooks (Sadler, 2004), the PAS reaches their maximum size during puberty. However, the literature reviewed differed in this regard. According to Jun et al. (2005), sex differences may exist regarding the age at which the maximum size of the PAS is attained. Wolf et al. (1993) described two active pneumatization phases between ages 4-8 years and ages 8-12 years with slow development between these phases. According to Wolf et al. (1993), all air sinuses reached their maximum size by ages 12-14 years with only few additional changes at ages 22-24 years when pneumatization was to be considered complete. Sanchez-Fernandez et al.'s (2000) study illustrated that the frontal air sinus increased with age until 30 years. The maxillary air sinus increased rapidly until 15 years with posterior growth occurring thereafter,

Table 5. Volumes of the paranasal air sinuses according to sex (mm^3).

Air sinus		RIGHT			LEFT		
		n	Mean ± std.	p-value	N	Mean ± std.	p-value
Frontal	Male	213	**3936.0 ± 3826.0**	**0.03**	216	4313.8 ± 3927.3	0.08
	Female	151	**3138.2 ± 2840.3**		156	3636.8 ± 3255.1	
Sphenoid	Male	254	3452.8 ± 3240.6	0.94	256	3498.1 ± 3187.8	0.40
	Female	188	2961.2 ± 2750.0		185	3254.6 ± 2700.5	
Maxillary	Male	274	9184.8 ± 6577.6	0.06	274	9278.3 ± 6750.1	0.08
	Female	203	8109.8 ± 5197.4		203	8270.7 ± 5326.5	
Ethmoid	Male	276	3649.9 ± 2277.4	0.28	275	3582.6 ± 2111.3	0.40
	Female	203	3433.5 ± 1938.0		203	3418.1± 2073.4	

Table 6. Volumes of the paranasal air sinuses according to population groups (mm^3).

Air Sinus		RIGHT			LEFT		
		n	Mean ± std.	p-value	N	Mean ± std.	p-value
Frontal	Black African	326	3617.4 ± 3558.7	0.84	334	4031.1 ±3 611.6	0.99
	White	38	3498.8 ± 2616.8		38	4019.4 ± 4212.4	
Sphenoid	Black African	396	3177.7 ± 3058.8	0.18	395	3231.4 ± 2932.9	**0.001**
	White	46	3811.5 ± 2924.1		46	4809.0 ± 3154.6	
Maxillary	Black African	430	8298.7 ± 5862.8	**0.001**	430	8474.0 ± 6008.0	**0.001**
	White	47	12648.7±6351.0		47	12275.5±6901.7	
Ethmoid	Black African	432	3563.3 ± 2192.8	0.87	431	3518.3 ± 2153.3	0.86
	White	47	3511.2 ± 1600.4		47	3462.0 ± 1467.7	

while the ethmoid and sphenoid air sinuses reached a maximum size by 15 years maintaining these averages. A study by Park et al. (2010) noted that the ethmoid and maxillary air sinuses were both present at birth for all cases in their study. All of the air sinuses except for the frontal reached maximum growth by age 15 years of age. The sphenoid air sinus exhibited a growth spurt between 6 to 10 years of age and also completed pneumatization by 15 years. The frontal air sinus aeration began from two years of age with a faster growth pattern between 6 to 19 years of age.

The current study illustrated growth patterns that appeared to change broadly across four phases. The patterns of the rate of growth of the air sinuses in this study illustrated similar trends to Park et al. (2010) with a few variations. Most of the air sinuses were present at birth, with a growth spurt around 7 to 9 years of age, rapidly increasing with age until 16 to 18 years of age. These findings illustrated that sinus growth spurts coincides with puberty [(which is eight years for females and nine years for males (Moore et al., 2016)], confirming a study by Gagliardi et al. (2004) that the air sinus are related to hormonal changes. However, these authors illustrated, in a study of the frontal air sinus and stature, that the peak growth of the air sinus may correspond with the growth spurts observed in stature, but, these peaks in growth of the air sinus occurred after the peaks in height of the individual. Peak growth in stature usually occurred around puberty (9 to 13 years of age).

In addition, it was noted that the maxillary air sinus bilaterally and left frontal air sinus could still increase beyond 25 years of age as supported by Jun et al. (2005) and Tatlisumak et al. (2008). Interestingly, the current study noted that the ethmoid and sphenoid air sinuses have identical growth curves, suggesting a common origin of this part of the PAS system, which is consistent with a study by Spaeth et al. (1997). This differed from Takahashi's work (1984), which suggested that the frontal air sinus and sphenoid air sinuses have similar growth, being resorption- type sinuses, which developed between osseous walls.

Sex and the paranasal air sinuses

In a study of maxillary air sinus growth from 1 to 70 years of age conducted by Jun et al. (2005), it was observed that the volume of the maxillary air sinus reached its maximum size at ages between 21 to 30 years in males, and between 11 to 20 years in females. In the study by Spaeth et al. (1997) of over 5600 CT scans, it was revealed that female air sinuses were larger until five to six years of age, and, thereafter this tended to reverse. The Karakas et al. (2005) study also confirmed sex differences. In the current study, sex differences were present viz. males tended to have larger volumes than females, but the mean volumes were not statistically significant. However, it would seem that these larger volumes in males were more apparent after 16 to 18 years of age. These findings are similar to Sanchez Fernandes et al. (2000) and Apuhan et al. (2011) in that sex differences may exist which are not statistically significant. However, interestingly, the right frontal air sinuses were significantly larger in males ($p=0.03$). This compared favourably with a study by Pirner et al. (2009). It may be suggested that perhaps the frontal air sinus differences may reflect sex differences in terms of the 3D form of the air sinuses or perhaps the dimensions of the cranium in the nasofrontal region may differ, and this may be contributed to the development of the frontal air sinus particularly. Therefore, further research is warranted.

Population groups and the paranasal air sinuses

As most studies reviewed different age groups, some below or above 25 years of age, mean bilateral volumes of the paranasal air sinuses at 16 to 18 years of age were compared, as this was the point at which pneumatization was complete within this study sample. The values obtained at 16-18 years of age were comparable with studies in the Turkish population (Apuhan et al., 2011). However, the air sinuses in the current study were larger in comparison to studies by Park et al. (2010), which evaluated the PAS of the Asian population. The sample within the current study was derived from a review of CT scans of patients within a South African population, ranging between 1 to 25 years of age. The test compared the mean volume of each paranasal air sinus in relation to the different population groups within the sample, and suggests that variations in terms of the air sinuses' volume exist, which may be attributed to ancestry (Table 6). However, in the current study the volume of the population groups was different in the maxillary air sinus and the left sphenoid air sinuses only ($p<0.001$). The current study supported the view of Fernandes (2004) in that the mean difference in the volumes of the maxillary air sinuses were statistically significant between the population groups ($p< 0.001$) rather than between the sexes ($p>0.05$). However, the sample within the Fernandes (2004) study consisted primarily of the adult group (mean age above 40 years) limiting its value for comparison in the younger age groups. Fernandes (2004) states that the volume of the PAS may be related to function, which still remains unknown.

CONCLUSION

This study presented data of the PAS of the South African populations using 3D reconstructed models. The data illustrated important morphometric volume growth of the paranasal air sinuses and variation according to age, sex, laterality and within the study population. It is apparent that a study consisting of a large sample of 3D models of the PAS has not been previously documented. The findings highlighted the development of all the air sinuses according to age utilising 3D reconstruction. In particular, the volume of the ethmoid air sinus from 1 to 25 years of age was documented, which was not fully reported. The study confirmed differences in terms of the paranasal air sinuses' size across populations, particularly the maxillary and sphenoid air sinuses, and sex differences viz. the right frontal air sinus. These findings add to existing data regarding the PAS, as well as, elaborating upon the standard norms of the paranasal air sinuses within the South African population. The study may be useful in otorhinolaryngology, forensic and comparative osteology.

REFERENCES

ADIBELLI ZH, SONGU M, ADIBELLI H (2011) Paranasal sinus development in children: A magnetic resonance imaging analysis. *Am J Rhinol Allergy,* 25(1): 30 -35.

APUHAN T, YILDIRIM, OZASLAN H (2011) The developmental relation between adenoid tissue and paranasal sinus volumes in 3 dimensional computed tomography assessment. *Otolaryn Head Neck Surg,* 144(6): 964-971.

AMUSA YB, EZIYI JAE, AKINLADE O, FAMEREWA OC, ADEWOLE SA, NWOHA PU, AMEYE SA (2011) Volumetric measurements and anatomical variants of Africans (Nigerians) using dried crania. *Intl J Med Medical Sci,* 3(10): 299-303.

BARGHOUTH G, PRIOR JO, LEPORI D, DUVOISM B, SCHNYDER P, GUDINCHET F (2002) Paranasal sinuses in children. *Eur Radiol,* 12: 1451-1458.

CHANG C, INCAUDO G, GERSHWIN M (2014*) Diseases of the Sinuses. A Comprehensive Textbook of Diagnosis and Treatment*. Springer, New York.

EMIRZEOGLU M, SAHIN B, BILGIC S, CELEBI M, UZUN A (2007) Volumetric evaluation of the paranasal sinuses in normal subjects using computer tomography: A stereological study. *Auris Nasus Larynx,* 34: 191-195.

FERNANDES CL (2004) Forensic ethnic identification of crania. The role of the maxillary sinus - a new approach. *Am J Forensic Med Path,* 25(4): 302-313.

GAGLIARDI A, WINNING T, KAIDONIS T, HUGHES T, TOWNSEND GC (2004) Association of the frontal air sinus development with somatic and skeletal maturation in Aboriginal Australians: a longitudinal study. *HOMO-J Comp Human Biol,* 55: 39-52.

JUN BC, SONG SW, PARK CS, LEE DH, CHO KJ, CHO JH (2005) The analysis of the maxillary sinus aeration according to the aging process; volume assessment by 3 dimensional reconstruction by high-resolutional CT scanning. *Otolaryngol Head Neck Surg*, 132(3): 429-434.

KARAKAS S, KAVAKLI A (2005) Morphometric examination of the paranasal air sinuses and mastoid air cells using computed tomography. *Ann Saudi Med,* 25 (1): 41-45.

KIM J, WHA SONG S, CHO J, CHANG K, JUN B (2010) Comparative study of the pneumatization of the mastoid air cells and paranasal air sinuses using three-dimensional reconstruction of computed tomography scans. *Surg Radiol Anat,* 32: 593-599.

LEE DH, SHIN J, LEE DC (2012) Three-dimensional morphometric analysis of paranasal sinuses and mastoid cell system using computed tomography in paediatric population. *Int J Paediatric Otolaryngol*, 76(11): 1642-1646.

PARK IH, SONG JS, CHOI H, KIM TH, HOON S, LEE SH, LEE HM (2010) Volumetric study in the development of the paranasal air sinuses by CT imaging in Asian: Pilot study. *Int J Pediatr Otorhinolaryngol*, 74 (12): 1347-1350.

PIRNER S, TINGELHOFF K, WAGNER I, WESTPHAL R, RILK M, WAHL FM, BOOTZ F, EICHHORN KW (2009) CT-based manual segmentation and evaluation of paranasal sinuses. *Eur Arch Otorhinolaryngol*, 266 (4): 507-518.

SADLER TW (2004) *Langman's Medical Embryology.* 9th Edition. Lippincott Williams and Wilkins.

SCUDERI AJ, HARNSBERGER HR, BOYER RS (1993) Pneumatization of the paranasal air sinuses: Normal features of importance to accurate interpretation of CT scans and MR images. *AJR Am J Roentgenol,* 160(5): 1101-1104.

SANCHEZ FERNANDEZ JM, ANTA ESCUREDO JA, SANCHES DEL REY A, SANTAOLALLA MONTOYA F (2000) Morphometric study of the paranasal sinuses in normal and pathological conditions. *Acta Otolaryngol.* 12: 273-278.

SHAH RK, DINGRA JK, CARTER BL, REBEIZ E (2003) Paranasal sinus development: a radiographic study. *Laryngoscope*, 113: 205-209.

SPAETH J, KRUGELSTEIN U, SCHLONDORF F (1997) The paranasal sinuses in CT-imaging: development from birth to age 25. *Int J Paed Otorhinolaryngol*, 39: 25-40.

TAKAHASHI R (1984) The formation of the paranasal air sinuses. *Acta Otolaryngol*, 408: 1-28.

TATLISUMAK E, OVALI GY, ASIRDIZER M, ASLAN A, OZYYURT B., BAYINDIR P, TARHAN S (2008) CT study on morphometry of frontal sinus. *Clin Anat*, 21: 287-293.

WOLF G, ANDERHUBER W, KHAN F (1993) Development of the paranasal sinuses in children: implications for paranasal sinus surgery. *Ann Otol Rhinol Laryngol*, 102(9): 705.

WOLFOWITZ (1974) Pneumatization of the skull in South African Negro. PHD thesis.

YUN IS, KIM YO, LEE SK, RAH DK (2011) Three dimensional computed tomographic analysis of frontal sinus in Asians. *J Craniofac Surg*, 22(2): 462-467.

www.slicer3D.org - accessed in December 2012.

Statistical release P0302. National population estimates. p7. [Accessed 25 August 2016] www.statssa.gov.za/publications/P0302/P03022016.pdf