The utility of three-dimensional models of paranasal sinuses to establish age, sex, and ancestry across three modern populations: A preliminary study

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ABSTRACT

Technological advances have furthered the development and understanding of trace materials such that DNA and fingerprints have become the foundation of human identification. However, when a body undergoes damage such as in cases of arson, these methods of identification may not be possible, and alternative methods of identification become critical. Previous studies have quantified the variability of the paranasal sinuses between individuals and have begun to explore their ability to provide biological information. However, the published literature investigating these structures in a forensic anthropology context offers variable findings. This study presents a new approach for establishing a biological profile using three-dimensional (3D) reconstructions of the paranasal sinuses. 3D models were produced from a database of modern CT scans provided by University College London Hospital (UCLH), London, UK. Elliptic Fourier and linear analysis produced from the 3D models demonstrated notable variations and patterns for discriminating age, sex, and ancestry across three distinct ethnic groups. The most promising classification rates ranged from 82.8% ($p=.027$) to 76.9% ($p=.003$) for age and sex prediction. The findings offer insights into the potential for using the paranasal sinuses as an attribute for discriminating between individuals and the identification of unknown human remains in crime reconstruction investigations.

KEYWORDS: Forensic Science, Forensic Anthropology, Victim Identification, Three-dimensional reconstruction, Paranasal Sinuses

Introduction

Human identification can be an essential element in a forensic investigation. A forensic anthropologist aims to assist law enforcement in establishing the biological profile to unknown remains using various metric and visual methods [1, 2]. These methods become crucial when human remains are severely damaged or burned and standard methods for positive identification such as DNA or fingerprints are not possible [3, 4]. However, the majority of traditional metric and non-metric methods used in the establishment of a biological profile by forensic anthropologists were developed using North American populations, and therefore have shown differing accuracy rates when applied to skeletal remains outside of the reference sample [1,5-9]. For example, MacLaughlin et al. [5] tested the reliability and accuracy of the Phenice [10] method for correct sex assessments on European adult skeletal remains and could not support the original results observed by Phenice[10]. Ubelaker et al.[6] also found that the experience of the observer contributed significantly to the accuracy of this method. Similar issues are presented in standard age estimations where only a limited number of studies have examined the reliability of these methods across Europe and fewer within the UK[11-14]. Methods based on modern populations are vital in order to validate and further improve the existing body of knowledge for both global and population-based methods[15]. Therefore, complementary studies that reflect modern UK populations are needed to support new and more sophisticated methods of measurement and analysis to ultimately aid in robust identifications[15-17].

Published research [18- 20] has quantified the variability of the frontal sinus between individuals and has likened the distinctiveness of this structure to that of fingerprint comparison. The variability of the frontal sinus between individuals has resulted in its successful use as a primary source for identification supported by expert testimony in the court of law [21, 22]. Previous studies have relied on a range of methods for analysis of the sinuses, including codifying certain features or acquiring measurements from radiographic data, such as computed tomography (CT) scans or X-rays [18, 23-25]. However, three-dimensional (3D) modelling is crucial in examining the paranasal sinuses due to its documented accuracy and utility in examining anatomical structures [26-28] and should be employed where possible. Therefore, utilizing 3D modelling to determine the effectiveness to paranasal sinuses in determining age, sex, and ancestry as a potential tool in establishing a biological profile is a valuable next step.

The existing published literature on the paranasal sinuses [29-33] include studies with varying emphasis on each sinus (frontal, maxillary, ethmoid and sphenoid) and are typically targeted towards practicing physicians for medical care and not explicitly intended for establishing sex, age, or ancestry to establish a biological profile. Consequently, research investigating the ability of the paranasal sinuses to provide biological information to ultimately assist with forensic identification of unknown human remains on modern UK populations could not be identified. Furthermore, methods developed from modern UK populations to assist with establishing a biological profile are essentially non-existent.

This paper presents a preliminary study that was developed to demonstrate proof of concept for developing a tool to assess the potential of these structures to provide biological information that includes age, sex, and ancestry indicators elicited from 3D models of paranasal sinuses on a modern UK population. Elliptic Fourier and linear analysis were employed on 120 three-dimensional paranasal sinus models produced from CT data of 30 individuals to determine if this approach was able to reveal notable patterns in size and shape that might exist to aid discrimination on the basis of age, sex, and ancestry across three ethnic groups. This study therefore aims to lay the foundation for establishing a new and reliable method to assist in the generating of biological profiles of a modern UK population in forensic anthropology through the use of computer-assisted methods for three-dimensional reconstructions of the paranasal sinuses.

Materials and Methods

Dataset

Three-dimensional models were produced from a database of modern clinical sinus CT scans from living individuals in the UK population provided by University College London Hospital (UCLH) London, UK. The sinus CT scans were anonymized prior to collection by the picture archiving and communications (PACS) department at UCLH with only age, sex, and self-assigned ethnic group provided. The CT scans were provided in DICOM (Digital Imaging and Communications in Medicine) imaging format at 1 mm slice thickness. This study was approved by the Health Research Authority (HRA) and was exempt from requiring further NHS REC approval by the HRA.

This preliminary study utilised the sinus-specific 3D modelling method developed by Robles et al.[34] to produce three-dimensional models of the paranasal sinuses. An initial sample of n=30 sinus CT scans were taken from a larger dataset created from a modern UK population (Table 1). A smaller sample size for this study was selected to demonstrate proof of concept of not only the capability and feasibility of the Robles et al.[34] method but to also assess the challenges and potential limitations of employing this method and any subsequent analysis at a larger scale. It was also undertaken to establish whether it was possible to identify potential trends in the data generated from the initial small sample set in order to establish a robust approach for a larger and more substantive study of the full dataset available. Similar sample sizes have been employed in numerous studies to determine populational variations in both pilot and full-scale studies [28,31,35-40]. A sample of 30 CT scans resulted in a sizable dataset as n=120 models were ultimately produced as each individual typically has four paranasal sinuses. The subsequent measurement and analysis of these models resulted in a considerable dataset of n=480 measurements (height, width, length and volume across 120 models) and a robust dataset of shape descriptors.

The sample dataset for this study consisted of 10 individuals from three different ethnic groups (White British, Black African, and Chinese) all of which were chosen randomly from the larger dataset provided by UCLH. The ethnic group assigned to each CT scan was self-reported by the patient. Uncertainty is a noted limitation when using self-reported ethnic groups and is inherent with this dataset. However, this is a baseline study to determine potential patterns between groups that might prove valuable in forensic reconstructions.

Male and female subjects were chosen from each ethnic group randomly with an equal number of each sex distributed within each group (see Table 1). Additionally, the size and shape of the sinuses may change with age due to pneumatisation [41, 42]. Therefore, the division of age groups was intended as a potential identifier in possible aging patterns and preliminary trends to inform future studies if age groups could be examined. Individuals were divided into a simple split between two age groups; <49 years and 50+ years. The database provided by UCLH included the ages of each individual in years, months not included. Consequently, individuals that fell between the ages of 49 and 50 were considered 49 years old. The selection of 49 years as a cut-off was selected for equal sample size distribution [43]. The sample excluded individuals with visible trauma or pathology to the sinuses.

Table 1. *Dataset composition*

Preliminary Dataset					
Number of Subjects (N=30)					
Ethnic Groups		**Sex**		**Age**	
		Male	*Female*	*<49 yrs*	*50+ yrs*
White British	10	5	5	4	6
Black African	10	5	5	6	4
Chinese	10	5	5	4	6
Overall	**30**	**15**	**15**	**14**	**16**

Data Collection and Processing

3D reconstructions were integral to the data collection process. The accuracy and precision of 3D models is well documented [27, 28, 44] and have been demonstrated to have significant value when examining the sinuses [20, 26,45] given the three-dimensional nature of the sinuses[26] in contrast to measurements taken from 2D images. There are a range of visualization programs that have the potential to produce three-dimensional models from CT scans. However, commercial visualization programmes are not always cost-effective or accessible across platforms [46]. Furthermore, there is no significant difference between models produced from commercial and open-source software [47]. Therefore, the open source software program *3D Slicer™* [46] was used to produce the three-dimensional models in this study. This software program is a DICOM viewer allowing for easy exportation and importation of STL (stereolithography) files to other platforms. Figure 1 presents the overall workflow employed in this study, from the production of the 3D models to the subsequent measurements and analysis.

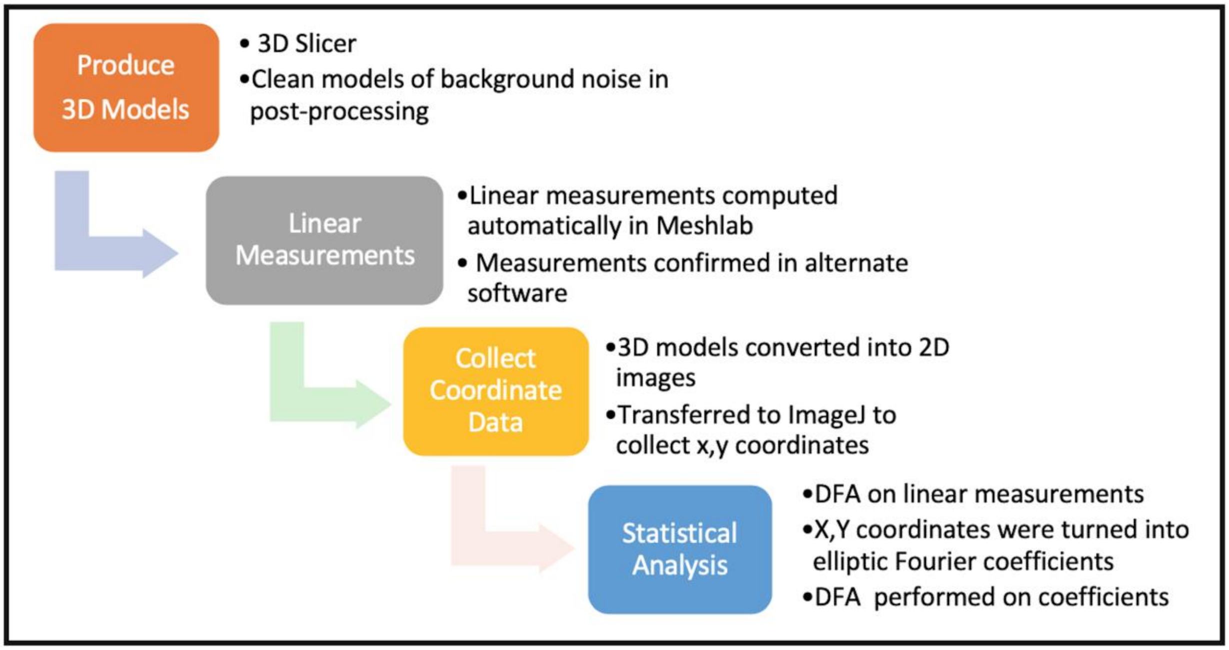

Figure 1. Process and workflow

First, the CT scans were imported into *3D Slicer™* following the method developed by Robles et al.[34] for importing; cropping; segmenting; and thresholding to produce the final 3D models of the paranasal sinuses. The Robles et al. [34] method requires the analyst to produce a model of each sinus separately for analysis as opposed to producing the paranasal sinuses at the same time allowing for a faster segmentation and thresholding process (see Robles et al., [34]). The method also allowed for individual analysis of each sinus to determine if one sinus provided more discriminatory capability in terms of biological patterns over others. The final three-dimensional models of each sinus (frontal, maxillary, ethmoid, and sphenoid) were then saved as an STL file. The STL file was then exported to *MeshLab™* [48] and *ImageJ™* [49] for subsequent measurement and analysis (see Figures 2 and 3).

Next, the measurements from each sinus model were calibrated automatically in Meshlab™ to ensure uniform, accurate and speedy analysis. Linear measurements including height, width, length, and total volume were recorded in millimetres on each model. The measurements were not taken manually, and landmarks were not employed but rather the dimensions of the models were automatically detected and recorded in Meshlab*™* (see Figure 2). Therefore, measurement validation between observers was not necessary as measurements were not collected manually. However, the measurements provided by Meshlab*™* were further confirmed in an alternate software program to ensure the measurements were consistent across platforms.

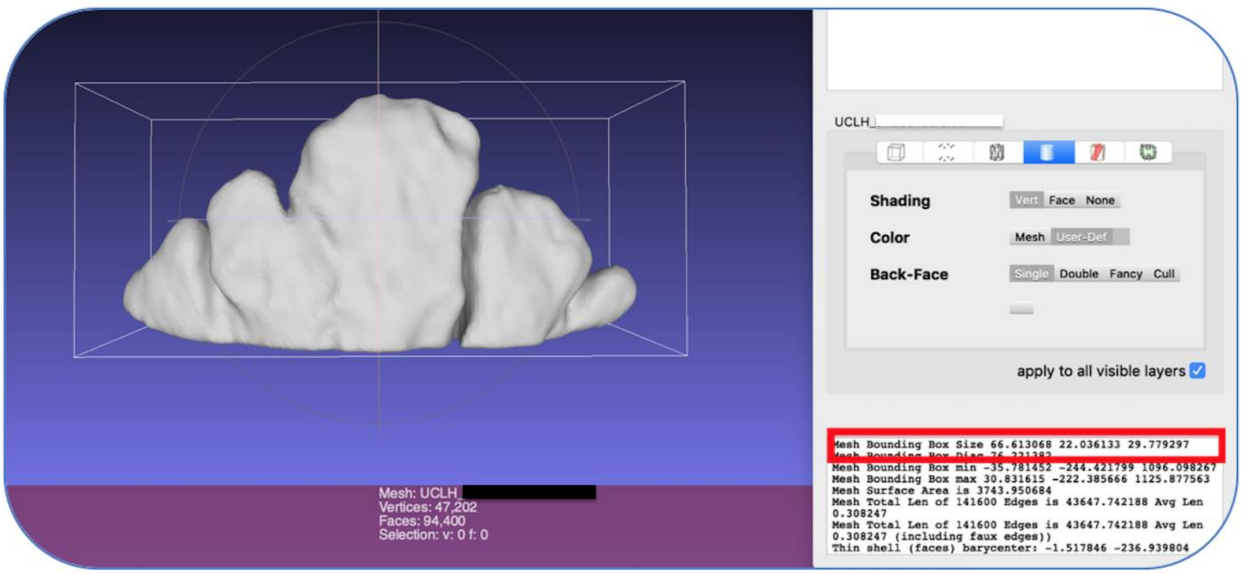

Figure 2. Measurements taken from three-dimensional model of a frontal sinus in Meshlab™.

Elliptic Fourier analysis (EFA) was then performed to determine if the outline shape of the 3D model of the frontal sinuses could provide more discriminatory variables to assist in establishing age, sex, and ancestry of the individual. EFA is a method that can capture the extreme variation of paranasal sinuses as it does not require homologues or equally spaced landmark points unlike other methods of morphological analysis [50]. The method is a mathematical tool developed to quantitatively describe a closed outline using sine and cosine terms [50, 51]. To carry out EFA, the coordinate data from the outlines of the 3D models were collected.

To collect the x,y coordinates for EFA, the 3D models were converted into 2D images and transferred to the free software programme *ImageJ™* where the outline coordinates of the sinuses were extracted. The 3D models were turned into 2D images in order to quickly and easily capture the outline of the 3D models rather than have to manually select and trace each sinus outline from a specific CT slice consistently across every individual CT dataset[18,23]. The images were then scaled and then turned into '*8-bit*' and made '*binary*' to accurately establish the outline of the sinus (see Figure 3).

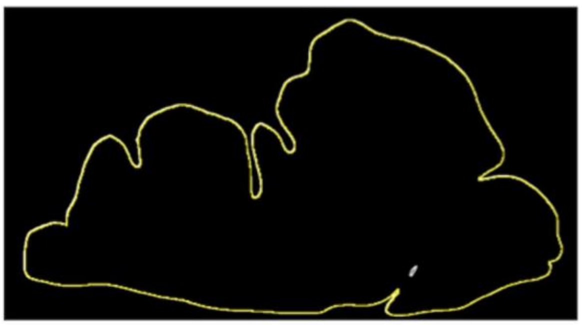

Figure 3. Outline of three-dimensional model of frontal sinus.

The coordinates were converted into elliptic Fourier coefficients to allow for statistical analysis [50, 52] to be undertaken on the shape data (see Figure 4) to directly compare the statistical results from the linear measurements and the elliptic Fourier coefficients. In this way it was possible to assess the degree to which the elliptic Fourier coefficients were able to act as discriminant independent variables.

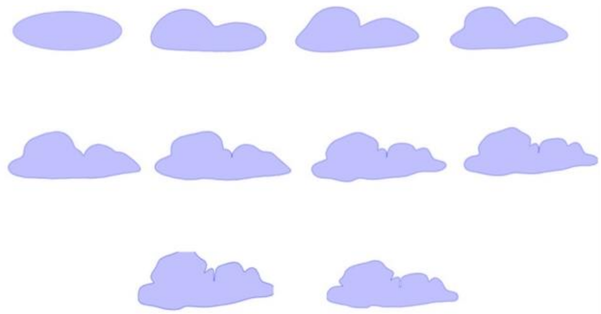

Figure 4. Harmonics of the frontal sinus.

The coefficients were produced in *Past3*^{TM} and were provided in sets of four where each set was defined as one *harmonic* in increasing order from 1 to 30. Figure 4 presents a depiction of increasing number of harmonics where each additional harmonic depicts a sharper and clearer approximation of the original sinus outline. The calculations in *Past3*^{TM}[53] also ensured that the coefficients were invariant to size and positional translation.

Data Analysis

The statistical software package IBM SPSS Statistics for Macintosh Software Version 26.0 (Armonk, NY:IBM Corp.) was used to undertake discriminant function analysis to determine how well the measurements of the sinuses act as predictors in correctly classifying the age, sex, and ancestry of the each individual. Fisher's linear discriminant function analysis (DFA) was applied as it is commonly used to assess whether skeletal measurements can correctly predict the elements of a biological profile [54, 55]. Furthermore, DFA derives rules from data that is classified into predetermined groups to assist with classifying new data on the basis of the observed variable values[55]. The test evaluates how well the discriminant function of the variables perform in their predictions by providing a classification rate. The classification rate is the number of subjects or cases correctly classified into the known sex, age, ethnic groups according to the discriminant rule, demonstrated by a percentage [56].

To mitigate for the small sample size[40] the statistical analyses were performed with bootstrapping (with 1000 bootstrap samples) at 95% confidence intervals (CI). Separate one-way ANOVA tests were included in the DFA output and were initially assessed to determine significant group differences. Depending on the significance of the one-way ANOVA results, DFA was then carried out on the linear measurements for each sinus model separately excluding major outliers. Following this, one-way ANOVA was carried out within each ethnic group to determine if there were significant differences between groups means.

DFA was also carried out (with bootstrapping with 95% CI) on the elliptic Fourier coefficients excluding major outliers. The outline measurements and subsequently the elliptic Fourier coefficients were only taken from the frontal sinus. This was to determine if outline analysis was a feasible form of measurement on these structures. The elliptic Fourier coefficients produced from the frontal sinus were tested against the entire sample (n=30) to determine age, sex, and ancestry using DFA. Due to the small sample size, the analysis was only run over the entire sample and not within each ethnic group.

Finally, the most discriminant variables that resulted with the highest classification rates from the linear measurements were analysed together with the elliptic Fourier Coefficients to determine if the classification results increased in the overall sample size. This was carried out to determine if using both forms of measurements (Linear and elliptic Fourier Coefficients) performed better at determining age, sex and ancestry than each form of measurement alone (see Figure 1).

Results

Biological Patterns of the Paranasal Sinuses

Descriptive statistics from each paranasal sinus measurement were analysed (bootstrapped at a 95% CI). The average mean and standard deviation of the linear and volumetric measurements between each sinus over the entire sample (n=30) are presented in Table 2. The results of the discriminant function analysis are provided in tables 3-21 wherein the one-way ANOVA; classification results; cross-validation results; p-values and other statistics are presented.

Table 2. Descriptive Statistics of the linear and volumetric measurements (mm).

Descriptive Statistics (mm)					
Bootstrapped (95% Confidence Interval)					
White British (N=10)		Height	Width	Length	Volume
Frontal Sinus	**Mean**	**19.86**	**18.26**	**56.41**	**4543.4**
	Std. Deviation	*6.34*	*5.05*	*12.04*	*3067.73*
95% CI	Upper	*23.67*	*21.15*	*63.13*	*6418.85*
	Lower	*16.08*	*15.19*	*48.84*	*2714.88*
Maxillary Sinus	**Mean**	**39.46**	**39.19**	**71.32**	**2472**
	Std. Deviation	*5.49*	*3.01*	*15.46*	*902.74*
95% CI	Upper	*42.73*	*40.85*	*78.57*	*3008.5*
	Lower	*36.49*	*37.47*	*59.87*	*1949.45*
Ethmoid Sinus	**Mean**	**29.65**	**35.6**	**33.97**	**4372.61**
	Std. Deviation	*6.28*	*4.51*	*4.65*	*2103.56*
95% CI	Upper	*33.36*	*38.28*	*36.98*	*5590.3*
	Lower	*26.23*	*32.91*	*31.44*	*3157.13*
Sphenoid Sinus	**Mean**	**26.22**	**29.31**	**33.14**	**12201.48**
	Std. Deviation	*3.59*	*5.77*	*5.96*	*16096.61*
95% CI	Upper	*28.34*	*32.62*	*36.8*	*23166.24*
	Lower	*24.21*	*25.74*	*29.55*	*5459.69*
Chinese (N=10)					

Frontal Sinus	**Mean**	**17.48**	**15.43**	**47.38**	**3305**
	Std. Deviation	*6.57*	*4.83*	*16.39*	*2032.85*
95% CI	Upper	*21.71*	*18.45*	*56.17*	*4554.79*
	Lower	*13.92*	*12.66*	*36.66*	*2124.05*
Maxillary Sinus	**Mean**	**39.56**	**38.73**	**83.06**	**3340.7**
	Std. Deviation	*8.08*	*3.63*	*11.98*	*1477.72*
95% CI	Upper	*44*	*40.74*	*89.68*	*4243.62*
	Lower	*34.45*	*36.47*	*75.59*	*2472.31*
Ethmoid Sinus	**Mean**	**26.2**	**37.02**	**37.37**	**5947.659**
	Std. Deviation	*5.34*	*4.57*	*4.39*	*1934.7319*
95% CI	Upper	*29.3748*	*39.5225*	*39.939*	*7224.77*
	Lower	*23.0475*	*34.237*	*34.8848*	*4902.31*
Sphenoid Sinus	**Mean**	**28**	**33.19**	**41.95**	**10872.698**
	Std. Deviation	*6.2*	*6.82*	*7.72*	*5264.38872*
95% CI	Upper	*31.85*	*37.01*	*46.57*	*13976.19*
	Lower	*24.6283*	*28.7119*	*37.5713*	*7756*
Black African (N=10)					
Frontal Sinus	**Mean**	**18.49**	**17.42**	**52**	**3689.1**
	Std. Deviation	*8.47*	*8.22*	*21.02*	*4423.4*
95% CI	Upper	*23.61*	*22.57*	*64.12*	*6458.76*
	Lower	*13.73*	*13.1*	*40.22*	*1490.1*
Maxillary Sinus	**Mean**	**42.14**	**43.34**	**85.51**	**3313.9**
	Std. Deviation	*6.49*	*4.94*	*8.57*	*1325.69424*
95% CI	Upper	*46.7044*	*46.3549*	*90.0293*	*4194.6908*
	Lower	*38.9931*	*40.5144*	*80.3359*	*2625.6229*
Ethmoid Sinus	**Mean**	**28.1**	**40.33**	**39.83**	**7733.34**
	Std. Deviation	*7.4*	*4.4*	*4.7*	*2506.55*
95% CI	Upper	*32.53*	*43.44*	*42.73*	*9196.7*
	Lower	*23.8*	*37.91*	*37.09*	*6174.03*
Sphenoid Sinus	**Mean**	**27.42**	**32.83**	**40.47**	**11647.679**
	Std. Deviation	*4.4*	*2.8*	*8*	*3929.86*
95% CI	Upper	*30.23*	*34.65*	*45.09*	*14175.04*
	Lower	*24.93*	*31.3*	*35.97*	*9416.46*

Frontal Sinus

The results of the one-way ANOVA and Welch test did not indicate significant differences between group means according to age or ethnicity ($p>0.05$). However, significant differences were seen in the group means according to sex ($p<.05$) (see Tables 3 and 4). DFA found that the frontal sinus measurements did not provide significant results in discriminating between sex ($p=0.06$) ($p>0.05$).

Table 3. One-way ANOVA results according to sex

Sex	df1	df2	F	Sig.
Height	1	25	9.962	0.004
Width	1	25	35.196	0

Table 4. Welch test for variables that violated test of Homogeneity of Variance

Robust Tests of Equality of Means (Welch)				
	Statistic[a]	df1	df2	Sig.
Length	12.802	1	15.887	0.003
Volume	13.972	1	16.455	0.002
[a] Asymptotically F distributed.				

Maxillary Sinus

Results from the one-way ANOVA (bootstrapped at 95% CI) did not show significance differences in the group means for any measurement variable across age ($p=.339$-$.888$) or sex ($p=.126$ -$.999$) ($p>0.5$) therefore additional analysis was not carried out. Significant differences were demonstrated according to ethnic group at the width variable ($p=.031$) ($p<.05$). However, the DFA results violated the Box's M tests of the null hypothesis of equal population covariance matrices ($p=0.008$) therefore the results of the DFA were not reliable.

Ethmoid Sinus

One-way ANOVA analyses indicated significant differences between mean measurements according to age where volume provided the most significant mean difference ($f_{1,27}$=6.927, p=0.014) (p<0.05). DFA was carried on these variables to classify age. Tables 5 provides the Eigenvalues and Wilks' Lambda with a significant p-value (p=0.027) which indicates the model is a good fit for the data. Tables 6 and 7demonstrate the variables that contributed most to the classification model. Table 8 provides the cut-score obtained by calculating the arithmetic mean of the centroid group values[55]. The application of this discriminant rule provided a classification rate of 82.8% (cross-validated 72.4%) (see table 9).

Significant differences of group means were not found according to sex (p>0.05) and no further analysis was undertaken.

Significant group differences were found according to ethnic group where volume provided a significant result ($f_{2,26}$=6.825, p=.0004). DFA found that measurements produced a low classification rate of 51.7 % (Cross-validated=48.3%) (p-value=.016) (p-value<.05). The corresponding output tables will not be listed as this classification rate, while significant, does not indicate an effective discriminating pattern.

Table 5. Summary of Canonical Discriminant Functions and Wilks' Lambda Statistics

Eigenvalues				
Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1	.551a	100	100	0.596
For split file bootstrap split=0, first 1 canonical discriminant functions were used in the analysis.				
Wilks' Lambda				
Test of Function(s)	Wilks' Lambda	Chi-square	df	Sig.
1	0.645	10.979	4	0.027

Table 6. Standardized Canonical Discriminant Function Coefficients

	Function	Coefficient	Bootstrap			
			Bias	Std. Error	95% CI	
					Lower	Upper
Height	1	-0.104	0.135	0.42	-0.884	0.779
Width	1	-0.009	0.124	0.354	-0.594	0.839
Length	1	-0.941	0.525	0.921	-1.698	1.401
Volume	1	1.372	-0.708	1.189	-1.827	1.917

a Unless otherwise noted, bootstrap results are based on 1000 bootstrap samples

Table 7. Canonical Discriminant Function Coefficients

	Function	Coefficient	Bootstrap			
			Bias	Std. Error	95% Confidence Interval	
					Lower	Upper
Volume	1	0.001	0	0.001	-0.001	0.001
Height	1	-0.017	0.024	0.074	-0.151	0.155
Length	1	-0.188	0.112	0.201	-0.341	0.338
Width	1	-0.002	0.029	0.079	-0.127	0.192
(Constant)	1	3.896	-4.096	5.958	-13.31	7.511

Unstandardized coefficients
[a] Unless otherwise noted, bootstrap results are based on 1000 bootstrap samples

Table 8. Functions at Group Centroids

Age Group	Function	Cut-off Score
	1	0.0745
<49 years	0.795	
50+	-0.646	

Unstandardized canonical discriminant functions evaluated at group means

Table 9. Classification results of the ethmoid measurements in classifying age group

		Age Group	**Predicted Group Membership**		**Total**
			<49 years	50+	
Original	Count	<49 years	11	2	13

		50+	3	13	16
	%	<49 years	84.6	15.4	100
		50+	18.8	81.3	100
Cross-validated	Count	<49 years	10	3	13
		50+	5	11	16
	%	<49 years	76.9	23.1	100
		50+	31.3	68.8	100
For split file bootstrap split=0, 82.8% of original grouped cases correctly classified.					
Cross validation is done only for those cases in the analysis. In cross validation, each case is classified by the functions derived from all cases other than that case.					
For split file bootstrap split=0, 72.4% of cross-validated grouped cases correctly classified.					

Sphenoid Sinus

One-way ANOVA did not show significant differences in groups means for any variable according to age (p=.305-.916) sex (p=.250-.933), or ethnic group (p=.053-.702) (p>0.05).

Intra-variability of Ethnic Groups - Linear Measurements

One-way ANOVA (bootstrapped at 95% CI) was run within each ethnic group to determine rates of intra-and inter-variability in determining age, sex, and ethnic group. The sample size of ten was not sufficient for discriminant function analysis.

Only the linear measurements of frontal sinus provided significant group differences for the White British and Chinese dataset (see tables 10 and 11). The Black African group did not provide significant differences in the groups means according to age or sex across all of the paranasal sinuses.

White British Dataset

Separate one-way ANOVA did not find significate differences in group means according age or ethnic groups across all of the sinuses in this group ($p>0.05$). However, significant group mean differences were found in the frontal sinus measurements according to sex (see Table 10)

Table 10. Width and height contribute to differences in groups means according to sex

	Sex			
	df1	df2	F	Sig.
Width	1	8	9.814	0.014
Height	1	8	6.42	0.035
Length	1	8	0.754	0.41
Volume	1	8	1.454	0.262

Chinese Dataset

One-way ANOVA analyses did not indicate significant differences in group means according age ($p>0.05$). Significant differences in groups means were found according to sex (see Table 11). Volume was not included in analysis as violated the assumption of non-multicollinearity. One-way ANOVA tests did not find significant mean differences for any other sinus (maxillary, ethmoid, or sphenoid) in this sample according to age or ethnic group ($p>0.05$)

Table 11. Width contributes to differences in groups means according to sex

	Sex			
	df1	df2	F	Sig.
Width	1	8	13.11	0.007
Height	1	8	1.609	0.24
Length	1	8	4.481	0.067

Black African Dataset

One-way ANOVA tests did not find significate differences in group means according to age or sex across all paranasal sinuses within this group ($p>0.05$).

Outline Measurements

One-way ANOVA tests showed significant differences in the groups means according to age (Siny3, $f_{1,28}$= 4.66, p=.04). However, further DFA did not find the discriminant function significant (p=0.121). One-way ANOVA tests found significant differences in the groups means according to sex (Siny1, $f_{1,24}$= 5.72, p= 0.025). However, this dataset failed the Box's M test of equal population covariance matrices (p=.006) therefore DFA was not carried out. One-way ANOVA tests found significant differences in the groups means according to ethnic group (Sinx2 Welch $_{1,11}$= 10.479, p= 0.002). However, DFA did not find this discriminant function significant (p= 0.376).

Linear Measurements and EFA coefficients

One-way ANOVA tests identified significant differences in groups means of the ethmoid volume and cosy 2 according to age ($f_{1,24}$= 4.522, p=.044) ($f_{1,24}$= 4.31, p=.049). These variables were then tested together in the DFA. DFA (bootstrapped with 95% CI) on these variables provided a significant p-value (p=.005)(p<0.05) (see Table 12). Tables 13 and 14 demonstrate variables that contributed to the discriminant function rule. Table 15 provided a cut-off score which provided a classification rate of 80.8% (cross-validated at 73.1%) (see table 16).

Table 12. Summary of Canonical Discriminant Functions and Wilks' Lambda Statistics

Eigenvalues				
Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1	.580[a]	100	100	0.606
For split file bootstrap split=0, first 1 canonical discriminant functions were used in the analysis.				
Wilks' Lambda				

Test of Function(s)	Wilks' Lambda	Chi-square	df	Sig.
1	0.633	10.527	2	0.005

Table 13. Standardized Canonical Discriminant Function Coefficients

	Function	Coefficient	Bootstrap			
			Bias	Std. Error	95% CI	
					Lower	Upper
Ethmoid Volume	1	0.893	-0.803	0.92	-1.223	1.247
Cosy 2	1	-0.883	1.058	0.905	-1.113	1.396
[a] Unless otherwise noted, bootstrap results are based on 1000 bootstrap samples						

Table 14. Discriminant Coefficients

Canonical Function

	Function	Coefficient	Bootstrap[a]			
			Bias	Std. Error	95% CI	
					Lower	Upper
Cosy 2	1	-4.154	5.255	4.645	-5.371	7.703
Ethmoid Volume	1	0	0	0	-0.001	0.001
(Constant)	1	-1.979	1.685	2.182	-3.272	2.791
Unstandardized coefficients [a] Unless otherwise noted, bootstrap results are based on 1000 bootstrap samples						

Table 15. Cut-off score based off Group Centroid functions

Age Group	Function	Cut-off Score
	1	
<49 years	-0.678	0.0565
50+	0.791	
Unstandardized canonical discriminant functions evaluated at group means		

Table 16. The classification results for classifying age groups

		Age Group	**Predicted Group Membership**		**Total**
			<49 years	50+	
Original	Count	<49 years	13	1	14
		50+	4	8	12
	%	<49 years	92.9	7.1	100
		50+	33.3	66.7	100

Cross-validated	Count	<49 years	13	1	14
		50+	6	6	12
	%	<49 years	92.9	7.1	100
		50+	50	50	100
For split file bootstrap split=0, 80.8% of original grouped cases correctly classified.					
Cross validation is done only for those cases in the analysis. In cross validation, each case is classified by the functions derived from all cases other than that case.					
For split file bootstrap split=0, 73.1% of cross-validated grouped cases correctly classified.					

One-way ANOVA tests showed potentially significant differences in the groups means in frontal sinus volume and cosx4 according to sex (Welch$_{1,20.2}$= 8.75, p=.008) (f$_{1,24}$=4.036, p=.056). These variables were then tested together in the DFA. Table 17 demonstrates a p-value that indicates the model is a good fit for the data (p-value=.003, p-value<.05). Tables 18 and 19 demonstrate the contribution each variable to the discriminant rule and final classifications. Table 20 provides the cut-off score which provided a classification result of 76.9% (cross-validated 76.9%) when classifying sex (see Table 21).

Table 17. Summary of Canonical Discriminant Functions and Wilks' Lambda Statistics

Eigenvalues				
Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1	.647[a]	100	100	0.627
For split file bootstrap split=0, first 1 canonical discriminant functions were used in the analysis Wilks' Lambda				
Test of Function(s)	Wilks' Lambda	Chi-square	df	Sig.
1	0.607	11.475	2	0.003

Table 18. Standardized Canonical Discriminant Function Coefficients

	Function	Coefficient	Bootstrap			
			Bias	Std. Error	95% CI	

					Lower	Upper
Frontal Sinus Volume	1	0.871	-0.231	0.609	-0.813	1.073
Cosx 4	1	-0.646	0.312	0.58	-0.928	0.924
a Unless otherwise noted, bootstrap results are based on 1000 bootstrap samples						

Table 19. Canonical Discriminant Function Coefficients

	Function	Coefficient	Bootstrap[a]			
			Bias	Std. Error	95% CI	
					Lower	Upper
Cosx 4	1	-8.962	3.751	8.435	-14.095	14.422
Frontal Sinus Volume	1	0	0	0	0	0.001
(Constant)	1	-1.112	0.194	0.899	-2.041	1.274
Unstandardized coefficients [a] Unless otherwise noted, bootstrap results are based on 1000 bootstrap samples						

Table 20. Cut-off score according to Group centroid Functions

Sex	Function	Cut-off Score
	1	0
Male	0.773	
Female	-0.773	
Unstandardized canonical discriminant functions evaluated at group means		

Table 21. Classification results of these variables in assigning sex

		Sex	**Predicted Group Membership**		**Total**
			Male	Female	
Original	Count	Male	8	5	13
		Female	1	12	13
	%	Male	61.5	38.5	100
		Female	7.7	92.3	100
Cross-validated	Count	Male	8	5	13
		Female	1	12	13
	%	Male	61.5	38.5	100
		Female	7.7	92.3	100
For split file bootstrap split=0, 76.9% of original grouped cases correctly classified.					

Cross validation is done only for those cases in the analysis. In cross validation, each case is classified by the functions derived from all cases other than that case.
For split file bootstrap split=0, 76.9% of cross-validated grouped cases correctly classified.

Discussion

This study evaluated 30 sinus CT scans by employing 3D modelling to determine if biological patterns exist using linear and elliptic Fourier analysis that could potentially aid in victim identification. Quantitative analysis of the 3D paranasal sinus models created for this initial study has demonstrated that there is potential in discriminating between individuals with regard to age and sex using the Robles et al.[34] method. These preliminary results also indicated that volume and shape analysis may provide the most discriminatory method for identification in determining age and sex.

One-way ANOVA of the frontal sinus measurements only provided significant mean differences according to sex, but not age or ethnicity. However, additional DFA did not find the model to be a good fit for the data. The maxillary sinus also provided similar results where group differences were not observed across age, sex, or ethnic group. The measurements from the ethmoid sinus provided a higher classification rate in predicting age at 82.8% (cross-validated 72.4%). The standardized canonical discriminant function coefficient table indicated volume provides the greatest contribution to the discrimination between groups. One-way ANOVA from the sphenoid sinus measurements did not indicate significant differences in groups means for any variable according to age, sex, or ethnic group ($p>0.05$) and therefore additional discriminant analysis was not carried out. This is in contrast to some studies that found the volume of the sphenoid sinus deviates with age [57, 58].

The results suggested that the White British and Chinese dataset may provide more discriminant variables in the frontal sinus according to sex than the Black African dataset.

However, as the sample sizes were too low to reliably measure intra-variability, this will need to be confirmed with greater sample sizes. It was also observed that the elliptic Fourier coefficients were less effective in determining the age, sex, or ethnic group alone. While one-way ANOVA found variables that contributed to significant differences in group means, DFA did not find these variables contributed to the discrimination between groups.

Discriminant function analysis demonstrated higher classification rates when certain volumetric measurements and the elliptic Fourier coefficients were analysed together. The one-way ANOVA of frontal sinus measurements indicated significant mean differences according to sex. Although these measurements did not provide significant classification results initially, when these measurements were tested with the EFA coefficients the classification results increased. The most notable results included the volume of the frontal sinus and EFA coefficient (Cosx 4) where the classification rate increased to 76.9% when predicting sex ($p<0.05$). This also occurred when the ethmoid volume and EFA coefficient (Cosy 2) were analysed together where the classification rate increased to 80.0% when predicting age ($p<0.05$). These results indicate higher classification results than reported for linear measurements in other studies[26,42,59-61]. However, these results along with the cut-scores provided are preliminary and will need to be confirmed with further research.

Although the discriminatory characteristics of sinuses have been identified in the previously published literature [18-20, 23-26, 29-33, 60 ,61] the complex anatomical structure of sinuses has provided significant limitations in terms of the ability to produce standardised methods of measurement across each paranasal sinus. The self-assigned ethnic group also provided a limitation in this study as it is difficult to ascertain how the individuals defined their ethnicity. However, this approach was based on modern UK populations (as opposed to historic collections) which ensures greater relevance for crime reconstruction approaches in contemporary forensic investigations. This study confirms the utility of the Robles et al.[34] method and the potential for reliable identification methods to be produced using computer-assisted methods considering three-dimensional reconstructions of the paranasal sinuses in establishing the biological profile in unknown modern skeletal remains.

Conclusion

This preliminary study sought to determine if the size and shape of the paranasal sinuses have the potential to determine age, sex, and ancestry in order to assist with establishing a biological profile to be used in crime reconstructions. The findings from this study showed that the volume and linear measurements of the frontal and ethmoid sinuses provided the highest classification rates when predicting sex and age over the entire sample. In addition, the volume of the frontal and ethmoid sinus showed classification rates increased when combined with EFA coefficients in predicting age and sex. The results also demonstrated that both forms of measurements were limited in their ability to predict ethnic groups. Furthermore, intra-variability was predominate in the White British and Chinese datasets in predicting age and sex, however the Black African dataset did not provide discriminant variables for any predetermined group. Finally, the measurements from the sphenoid sinus did not provide discriminant results that could assist with establishing a biological profile.

The key development of this preliminary study was the validation of the three-dimensional reconstruction method that facilitated and supported accurate data collection. This preliminary study also indicates that the paranasal sinuses may be able to offer valuable discriminatory characteristics that can be deployed in reconstruction approaches. However, further studies are needed to test and explore the capabilities of this approach with a larger dataset that also includes additional ethnic groups which will be the basis of a future study that utilises the full dataset available.

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