



An innovative 3D-3D superimposition for assessing anatomical uniqueness of frontal sinuses through segmentation on CT scans

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Abstract

Anatomical uniqueness plays a significant role in the personal identification process of unknown deceased. Frontal sinuses have been widely used in the past decades for this purpose, mostly using 2D X-ray techniques. However, the modern 3D CT-based segmentation methods may help in developing novel and more reliable methods of identification. This study aims at assessing the anatomical uniqueness of frontal sinuses through the 3D model registration. Thirty subjects who underwent two maxillofacial CT scans (interval: 1 month to 5 years) were selected from a hospital database. Frontal sinuses were automatically segmented through ITK-SNAP open source software and the 3D models belonging to the same patient were automatically superimposed according to the least point-to-point difference between the two surfaces. Two hundred patients were randomly selected from the same database and undergo the same procedure to perform 200 superimpositions of frontal sinuses belonging to different individuals, equally divided between males and females (mismatches). Statistically significant differences of average root mean square (RMS) point-to-point distance between the group of matches and mismatches, as well as possible differences according to sex, were assessed through Mann-Whitney *U* test ($p < 0.05$). In the group of matches, RMS ranged between 0.07 and 0.96 mm (mean RMS 0.35 ± 0.23 mm), while in the group of mismatches, it ranged between 0.96 and 10.29 mm (mean RMS 2.59 ± 1.79 mm), with a statistically significant difference ($p < 0.0001$). Neither the matches nor the mismatches group showed statistically significant differences according to sex. This study proposes a novel 3D approach for the assessment of anatomical uniqueness of frontal sinuses, providing both morphological and quantitative analysis, and a new method of identification based on 3D assessment of frontal sinuses, applicable when ante-mortem CT scans are available.

Keywords Personal identification · Frontal sinuses · 3D segmentation · CT scan · Volumetric analysis

Introduction

The main identification methods are mostly based on DNA, fingerprint and dental analyses, being the latter particularly conducted through a radiological comparative approach [1]. However, in forensic practice, other anatomical structures have been widely used for reaching personal identification through their well-known anatomical uniqueness, resulting remarkably reliable. Frontal sinuses represent a perfect example and have been used since years for personal identification in forensic medicine and anthropology.

From an anatomical point of view, frontal sinuses are pneumatized structures, anterior to the ethmoid bone, extending for a variable distance between the exterior and interior portion of the frontal bone plates: they are usually bilateral, separated by a septum or not, with consequent confluence of both air spaces into a common one [2].

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They are typically asymmetric and are further divided by incomplete accessory septa into several recesses, communicating with each other [3].

Usually, the frontal sinuses appear at 1 year of age and show a progressive development, become radiographically detectable at 5–6 years and progressively increase in size, especially after puberty, reaching the final configuration at 20 years [3–5]. Unilateral and bilateral agenesis are rare in the general population, the former one ranging from 1.22 to 5.66%, and the latter one from 0.73 to 8.32% [6].

Frontal sinuses represent one of the most interesting parts of human body, thanks to their wide variability and individuality in shape and size [7]. In fact, even homozygotic twins have different frontal sinuses [8], and this anatomical property renders frontal sinuses so important for personal identification, when ante-mortem antero-posterior cranium X-ray images are available [9].

With time, several authors have attempted at assessing the anatomical uniqueness of frontal sinuses through different approaches: an example is provided by Yoshino et al. who in 1987 proposed a classification of frontal sinuses according to size, shape, asymmetry, outline of the superior border, presence of accessory septa, possible presence of supraorbital cells and invasion of orbital areas, resulting in a total number of more than 20,000 possible combinations [10], which is still restrictive of the highly complex and detailed individuality of these structures.

Another approach was to calculate inter-observer error between several operators in correctly matching radiographic images of frontal sinuses belonging to the same individual: some experiments of this type show percentages of repeatability close to 100% [11, 12]. These data merely confirm the high individuality of frontal sinuses, but they give no indications concerning the metrical and morphological differences between the same structures belonging to the same or different individuals.

The uniqueness of the image of frontal sinuses was firstly assessed by Christensen using an elliptical Fourier analysis of their contours: the study proved mathematically the variability of these structures, but only for what concerns the two-dimensional projection of their outlines, as on X-ray examinations [13], and did not consider their three-dimensional variability.

Another approach was based on the metrical assessment of frontal sinuses through the measurements of several metric parameters [12, 14]: however, these attempts are limited by the observation that many metrical traits are dependant one upon another, and therefore cannot be used for a combined probability analysis [15]. In addition, the metrical assessment of frontal sinuses does not give any indication concerning the morphological variability.

A major limitation of several studies concerns the assessment of frontal sinus variability on X-ray examinations which

can provide only a two-dimensional visualisation: from this point of view, the progressively increasing application of CT scans may give a novel impulse to this field or research, thanks to the possibility of exploring the same structure on different planes. In addition, CT scan enables researchers to perform segmentation of volumes, acquiring 3D models of the elements of interest [16]. The acquisition of the 3D model of frontal sinuses may provide more detailed and precise indications for the assessment and quantification of their anatomical uniqueness. Besides, in all medical sectors, the intensive use of CT scan technology for early diagnosis and care is progressively determining an increasing availability of this type of medical examination as ante-mortem material for personal identification. Some attempts at applying the modern techniques of 3D segmentation on CT-scans already exist: Cossellu et al. verified the high repeatability of measurements performed on 3D models of segmented frontal sinuses [17]. In addition, in 2013, Kim et al. applied a morphological and metrical classification to frontal sinuses segmented from CT scans of 119 subjects: only two individuals shared the same characteristics [18].

This study aims at exposing an innovative procedure for the assessment of frontal sinuses individuality, based on a 3D-3D superimposition procedure. The results may provide a new point of view for the assessment of individual variants affecting this anatomic structure.

Materials and methods

A database of 600 head CT scans was used to select a group of 30 subjects (15 males and 15 females) who underwent two maxillofacial CT scans in a time ranging from 1 month up to 5 years. CT scans derived from Picture Archiving and Communication System (PACS) of a hospital in Northern Italy. The most frequent clinical requests for CT scan were screening for cranial fractures in traumatic injuries (57.3%), sinusitis or nasal and paranasal symptoms (20.0%) and neurological symptoms (12.7%). Patients affected by craniofacial deformities, previous or recent traumatic events, frontal sinusitis and cases of monolateral and bilateral agenesis of frontal sinuses were excluded from the study. The age of the recruited subjects ranged between 20 and 90 years (mean age 55 years; SD 21 years). All CT scans were anonymized. The observational study was performed according to local and international ethic rules.

All CT scans were performed on a second-generation dual-source scanner, Somatom Definition Flash (Siemens, Forchheim, Germany), parameters of acquisition: kV 100, mAs 130, collimation 128×0.6 mm, rotation time 1.0 s, reconstruction thickness 3 mm. The segmentation procedure was performed on hard kernels.

The segmentation of frontal sinuses from the 30 selected patients was made through ITK-SNAP open-source software which allows to perform automatic segmentation of volumes according to grey levels [12]. The segmentation often included also parts of the superior nasal meatus; therefore, the inferior limit of the sinus was set at the ostium (Fig. 1). Repeatability of the procedure of segmentation was already verified by a previous publication [19]. The 3D models of the frontal sinuses were exported in .stl format files and then analysed through a 3D elaboration software (VAM© software, version 2.8.3, Canfield Scientific Inc.).

The 3D models of frontal sinuses extracted from CT scans of the same individual were then automatically superimposed according to the least point-to-point difference between the two surfaces. The obtained 30 superimpositions represented the group of matches (15 males and 15 females). Two hundred patients, equally divided between males and females, aged between 18 and 99 years, were randomly selected from the same database and paired up to undergo the same procedure: in this case, 200 superimpositions were performed between 3D models of frontal sinuses belonging to different individuals of the same sex (100 for males and 100 for females) and represented the group of mismatches (Fig. 2).

Once the registration between the two models was obtained, the software was requested to calculate the average and RMS (root mean square) point-to-point distance, expressed in mm. The calculation of distance between the two 3D models provided also a chromatic visualisation of areas with surface

differences, with areas coloured in blue, green and red: blue and red showed the areas more affected by differences between the models, whereas the unchanged areas were reported in green.

Statistical analysis was performed using SPSS (IBM SPSS Statistics for Windows, Version 22.0, IBM Corp).

Kolmogorov-Smirnov analysis was used to verify the normal distribution of average point-to-point distance and RMS values ($p < 0.05$); possible statistically significant differences in both measurements between males and females and between matches and mismatches were assessed through Student's t test for independent groups in case of normal distribution; otherwise, Mann-Whitney U test was applied. In both cases, a significance level of 5% was stated.

Results

Average point-to-point distance between 3D models was 0.05 mm (SD 0.23 mm) for matches and 1.16 mm (SD 1.79 mm) for mismatches.

In the group of matches, RMS values ranged between 0.07 and 0.96 mm, with an average RMS of 0.35 mm (SD 0.23 mm). On the other side, the group of mismatches gave RMS values between 0.96 and 10.29 mm with an average value of 2.59 (SD 1.79 mm) (Table 1, Fig. 3). The average point-to-point distance and RMS values in both groups were not normally distributed ($p < 0.05$). Neither the mismatches

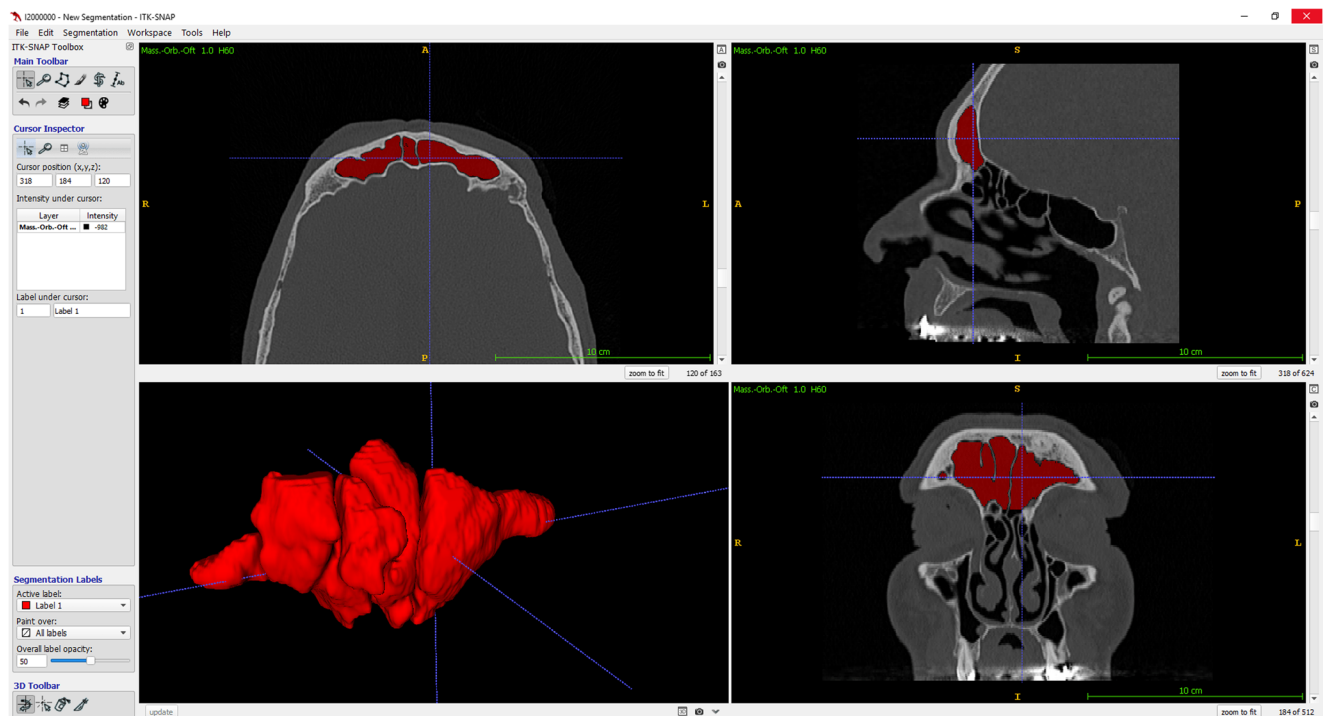
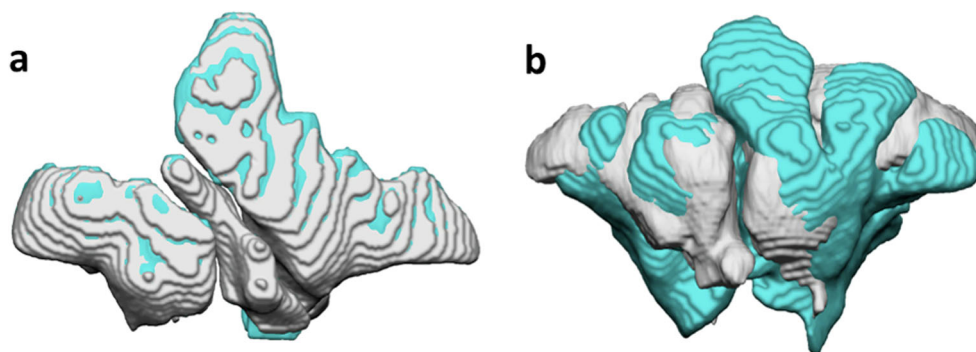


Fig. 1 Example of 3D segmentation through ITK-SNAP software: visualisation of frontal sinuses in the three axes and reconstruction of the segmented model in the lower left square

Fig. 2 Example of registration of two 3D models (respectively in white and light blue) of frontal sinuses belonging to **a** the same individual (match) and **b** different individuals (mismatch)



nor the matches group showed statistically significant differences according to sex for any measurement ($p > 0.05$).

On the other hand, both the average and RMS point-to-point distances showed statistically significant differences between the groups of matches and mismatches according to Mann-Whitney U test ($p < 0.0001$). The two groups superimposed only in one comparison, corresponding to the RMS value of 0.96 mm.

Discussion

The anatomical uniqueness is the property of anatomical structures to be unique in size and shape within a population and is a consequence of their random development: in fact, even homozygotic twins share the same DNA, but have different anatomical elements, such as frontal sinuses [20] and odontological profiles [21]. The anatomical uniqueness of the frontal sinuses has been already known and is determined by the wide variability of these pneumatized structures: in addition, frontal sinuses do not appreciably change with time until old age, when an increased pneumatization may occur because of atrophic changes [5]. Thanks to their wide inter-individual differences, the morphological and metrical analysis of frontal sinuses finds a practical application in personal identification of unknown deceased [9]; therefore, several authors have

attempted at assessing the anatomical characteristics of uniqueness of frontal sinuses, to extract possible methods for the identification of skeletal remains [9].

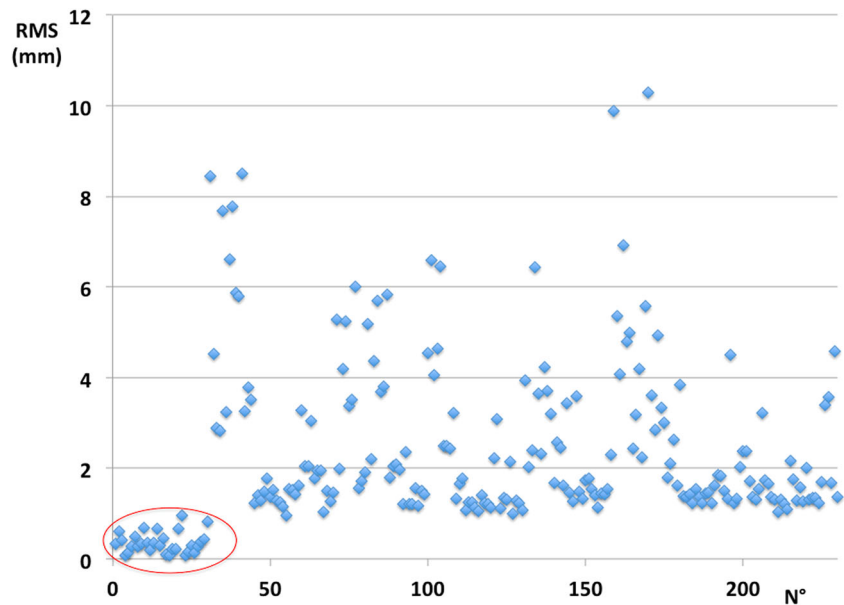
However, most of these approaches are not always respectful of the anatomical complexity of frontal sinuses, with a consequent underestimation of their uniqueness in shape and size. For example, some authors tried to include anatomical features of frontal sinuses within categories concerning the presence of accessory septa, asymmetry and morphology [10]: results show that the possible combinations can hardly describe the complexity of unique features of these structures. The same comment is valid also for studies concerning the metrical assessment of frontal sinuses, as they again include the population within categories, no longer based on morphological characteristics, but on metric ones [12, 14]. Another approach passes through the assessment of agreement in correctly matching images of frontal sinuses [11, 12]; however, this type of experiment confuses the anatomical uniqueness with the inter-observer error in its assessment and is not anatomically adherent to the specific characteristics of frontal sinuses.

The potential of 3D models of frontal sinuses is beyond the mere application of traditional classifications already applied to X-ray examinations: 3D models of frontal sinuses can be superimposed, starting from anatomical landmarks, to verify their point-to-point distance. This approach based on 3D

Table 1 Means, standard deviation values and results of Mann-Whitney U test for average and RMS point-to-point distance from the matches and mismatches group, divided according to sex

		Average point-to-point distance (mm)			Mann-Whitney U test
		Males	Females	Total	p
Matches	Mean	-0.01	0.10	0.05	< 0.0001
	SD	0.19	0.25	0.23	
Mismatches	Mean	1.24	1.08	1.16	< 0.0001
	SD	1.91	1.67	1.79	
		RMS point-to-point distance (mm)			Mann-Whitney U test
		Males	Females	Total	p
Matches	Mean	0.36	0.35	0.35	< 0.0001
	SD	0.18	0.27	0.23	
Mismatches	Mean	2.70	2.48	2.59	< 0.0001
	SD	1.89	1.69	1.79	

Fig. 3 Dispersion sheet of RMS values: matches are indicated by the circle; RMS: root mean square point-to-point distance



models has already been applied to the field of facial anatomy, for the analysis of uniqueness and movements due to mimicry [22, 23] and may provide an innovative quantitative assessment of frontal sinuses uniqueness, based on differences observed between 3D models belonging to the same individual and from different subjects.

A pilot study concerning this topic was performed by Beaini et al. in 2015: they segmented volumes of frontal sinuses from 20 CBCT scans and verified the reproducibility of correct match of 3D models belonging to the same individual, based on the mean point-to-point distance between the two surfaces. In 100% of cases, the two operators correctly identified the frontal sinuses belonging to the same individual [24]. However, no indication was given concerning the same metrical parameters in cases of superimposition of two models belonging to different individuals. Therefore, a quantitative assessment of anatomical uniqueness of frontal sinuses based on 3D segmented models has not been developed yet.

In addition, the importance of a novel method for personal identification based on 3D segmentation is urging, also in consideration of the widespread diffusion of CT scan technologies in the world [25–27]: during 2015, every 1000 inhabitants, 245.3 CT scans were performed in the USA [28], and in 22% of cases, they concerned the head district [25]. As a consequence, CT scans are expected to gain a growing importance as ante-mortem material in cases of personal identification.

The present results provide innovative hints for the analysis of unique characteristics of the pneumatized regions of frontal bones: in detail, the chromatic map of concordant and discordant areas is an interesting tool for evaluating which portion of sinuses are most different and may provide an immediate visualisation of the possible match between two models.

Secondarily, the metrical analysis of point-to-point distances between the two models may provide a quantitative information for personal identification, as both the average and RMS values were significantly different between the matches and mismatches group. The two measurements have a different importance: average point-to-point distance is the arithmetic mean of point-to-point distances where the positive (corresponding to areas where a reference 3D model is more prominent than the other one) and the negative ones (corresponding to zones where a reference 3D model is less prominent than the other one) elide each other. On the other side, RMS value is the root of the mean square of the same point-to-point distances which so become all positive. Therefore, RMS value provides a more complete information concerning the morphological discordance between 3D models of frontal sinuses than the average value, as it gives back a quantity which takes into account all the distances without considering which model exceeds the other one.

From this point of view, RMS value may provide a quantitative parameter for assessing differences between the 3D models, thanks to the statistically significant differences observed between the group of matches and mismatches: in the former case on average, the RMS value was 0.35 mm, whereas in the latter one, it was almost eight times higher. In addition, the groups of matches and mismatches did not overlap but for a single comparison out of 230: therefore, the 3D segmentation and registration of three-dimensional models of frontal sinuses seem to improve the assessment of morphological uniqueness. As a consequence, results may, once further corroborated, be used for assessing personal identification where ante-mortem cranium CT scans are available: an arbitrary RMS threshold of 0.96 mm (corresponding to the minimum of

mismatches and the maximum of matches) may be used for discriminating between positive and negative identification.

From this point of view, the use of registration methods and RMS calculation may provide an innovative approach for the assessment of differences of 3D structures, as already seen in studies focusing on facial anatomy [19, 20]. The proposed procedure has also the advantage of being based on CT scan acquisitions, whose frequency is growing in the world; in the future, personal identification methods will face the need of taking into consideration this type of radiological examination [29]. For what concerns post-mortem material, the diffusion of “virtopsy” practice has led to an increasing application of CT scans to forensic practice in different fields of analysis [30], including personal identification [31].

In conclusion, this study first applied modern 3D image acquisition and elaboration systems for the assessment of anatomical uniqueness and the development of a novel method based on 3D-3D surfaces registration.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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