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Frontal Sinuses for Identification: Quality of Classifications, Possible Error and Potential Corrections

ABSTRACT: Many studies have examined the characteristics of the frontal sinuses and their use for forensic purposes, particularly when an individual is edentulous. One of the most widespread classification systems is that proposed by Yoshino et al. The aim of this study was to improve the performance of Yoshino's method for identifying unknown skeletal remains by replacing the first two morphological items, frontal sinus size and bilateral asymmetry, by $SOR_1 =$ left frontal sinus area/left orbit area, and $SOR_2 =$ right frontal sinus area/right orbit area. According to the bivariate distribution of $SOR = (SOR_1, SOR_2)$ and available data, we also estimated the probability of positive misclassification.

KEYWORDS: forensic science, frontal sinus, personal identification, identification probability, forensic anthropology

Comparison of antemortem and postmortem records is a very important procedure in identifying individuals. Many parts of the skeleton can be used for this purpose: teeth above all, but also shoulder (1), skull (2), sphenoid sinus (3), sella turcica (4) and frontal sinuses.

The frontal sinuses are bilateral anatomical structures anterior to the ethmoid notch, and are unique in each individual, even in monozygotic twins. They extend for a variable distance between the outer and inner bone tables of the frontal bone and sometimes penetrate the orbital plates. They are not visible at birth, but begin to develop during the second year of life, are radiographically apparent at 5 years of age, and continue to grow slowly until puberty. Although their anatomy remains stable throughout life, physiological or pathological changes (individuals under 18 years of age, elderly persons, trauma, surgery, infection) and technical problems in radiography (distance between skull and film-tube, and its orientation) can modify the radiographic marks of a skull.

Many studies have examined the characteristics of the frontal sinuses and their use for forensic purposes (5,6), particularly when an individual is edentulous.

In 1987, Yoshino et al. (7) proposed a system of classification of the frontal sinuses based on the following morphological characteristics: area size, bilateral asymmetry, superiority of area size, outline of superior borders, partial septa, and supraorbital cells. This system assigns a class number to each morphological characteristic and the frontal sinus patterns of a given person are formulated as a code number obtained by arranging the class numbers in each classification item as serial numbers. If the morphological characteristics are considered as independent variables with uniform distribution in the population, then there is a probability of 1 in 23,040 that two different individuals will have identical code numbers.

However, frontal sinus marks seem to be significantly correlated and consequently the class numbers in each classification item are not independent, i.e., the possibility that two persons have similar frontal sinus patterns turns out to be greater. Furthermore, the relative frequency of the unilateral absence of a sinus is extremely low, and hence may be helpful in characterizing subjects with only one sinus (8).

Personal identification in forensic cases is carried out by X-ray work and the distinctive patterns of the frontal sinuses (9–13). Some authors have also studied the use of computerized axial tomography (CAT) for identifying marks on frontal sinuses (14).

A study of 39 cases of skeletal identification using the frontal sinus region (13) demonstrated its importance. Although the interval between antemortem and postmortem radiographic examinations, age, sex, and cause of death did not affect the ability to recognize a correct match, some difficulties still remain. The frontal sinuses develop until 18–20 years of age, the region may be altered by surgery, trauma, infection etc., advancing age can lead to sinus enlargement, and the distance between skull and film-tube, and its orientation, can also lead to mismatches between two X-rays of the same skull. The technique has several drawbacks, which include no empirical testing, estimates of potential error rates, standard controlling operational technique, or objective standards for determination (13). In some instances, these shortcomings may prevent conclusions from being admissible evidence.

In the USA, the Supreme Court has adopted the "Daubert Guidelines" (Table 1) to identify some of the factors relevant in determining whether evidence is scientifically based (15).

In the present study, the importance of Yoshino's identification system is confirmed, possible errors in comparisons between antemortem and postmortem X-rays are examined, and potential corrections are proposed. An attempt at estimating the probability of misclassification is also made.

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TABLE 1—*Daubert Guidelines for determining whether evidence is scientifically based and therefore admissible under Federal Rule.*

1. The content of the testimony can be (and has been) tested using the scientific method.
2. The technique has been subject to peer review, preferably in the form of publication in peer reviewed literature.
3. There are consistently and reliably applied professional standards and known or potential error rates for the technique.
4. Consider general acceptance within the relevant scientific community.

Materials and Methods

Radiographic images of the skulls of 98 Italians (41 women, 57 men) aged between 17 and 98 years were analyzed. X-rays were digitalized and images were recorded in a computer file. Radiographic images of frontal sinuses, which were usually radiographic apparent, were processed using a computer-aided drafting program (Adobe Photoshop 7). As described by Yoshino et al., these X-rays were used to evaluate frontal sinus areas (left and right sides), bilateral asymmetry, superiority of size, outline of the upper border of the left and right sinuses, partial septa, supraorbital cells and the orbital areas. As such images may differ significantly, according to the position of the skull in the X-ray beam, an attempt was made to reduce this potential source of error in frontal sinus size by estimating the ratios SOR_1 (left frontal sinus area/left orbit area) and SOR_2 (right frontal sinus area/right orbit area), instead of the frontal sinus areas directly.

Following Yoshino, the frontal sinus pattern of a given person was formulated as a code number, obtained by arranging in the following order: frontal sinus size, bilateral asymmetry, superiority of side, Ss, outline of the upper border (left, Ou_1; right, Ou_2), partial septa, Ps, and supraorbital cells, Sc.

Frontal sinus size was estimated as the sum of the areas of both the left and right sinuses and was classified into 4 categories (Table 2).

The classification of bilateral asymmetry of frontal sinuses was based on the formula for the asymmetry index:

$$\text{Asymmetry Index} = \frac{\text{smaller sinus area}}{\text{larger sinus area}} \times 100.$$

The bilateral asymmetry was classified into 4 categories as shown in Table 3.

TABLE 2—*Classification of area of frontal sinuses and relative frequency distribution of area size in samples.*

Area Size	Range (cm^2)	Relative Frequency (%)	Class Number
Small	0–6	13	1
Middle	6–12	44	2
Large	12–18	36	3
Very large	>18	7	4

TABLE 3—*Classification of the degree of bilateral asymmetry in frontal sinuses and relative frequency distribution of degree of bilateral asymmetry in samples.*

Degree	Range of Asymmetry Index	Relative Frequency	Class Number
Symmetry and almost symmetry	100–80	28	1
Slight asymmetry	80–60	28	2
Moderate asymmetry	60–40	24	3
Strong asymmetry	40–20	13	4
Extreme asymmetry	<20	7	5

TABLE 4—*Classification of the outline of upper border of frontal sinuses and relative frequency distribution of the outline of upper border in samples.*

	Relative Frequency		
Outline of Upper Border	Left	Right	Class Number
Absent	13	11	0
Smooth	28	40	1
Scalloped with 2 arcades	33	23	2
Scalloped with 3 arcades	24	20	3
Scalloped with 4 arcades	0	5	4
Scalloped with 5 arcades	2	1	5

TABLE 5—*Classification of the presence or absence of partial septa and of supraorbital cells and relative frequency distribution of them in samples.*

	Partial Septa %	Supraorbital Cells %	Class Number
Absent	58	70	0
Present in left side	14	15	1
Present in the right side	18	12	2
Present in the both sides	10	3	3

Bilateral asymmetry is 55% on left, and 45% on right.

Besides the bilateral asymmetry of the frontal sinuses, Yoshino used the unilateral superiority of area size as an item of classification of sinus pattern. Its class number was defined as follows: $\mathrm{Ss} = 1$ if the left sinus was superior to the right one, $\mathrm{Ss} = 2$ in the reverse case.

The outline of upper border of frontal sinus in each side was divided into 6 categories (Table 4) and the presence or absence of partial septa and of supraorbital cells was classified into 4 categories as shown in Table 5.

In the attempt to improve the performance of Yoshino's method for identification of unknown skeletal remains, we subsequently considered e new system of classification of the frontal sinuses based on the following morphological characteristics: SOR_1 and SOR_2, instead of the area size and bilateral asymmetry of the Yoshino's method, and superiority of area size, outline of superior borders, partial septa, and supraorbital cells. The frontal sinus pattern of a given person was thus classified according to the bivariate continuous variable $\mathrm{SOR} = (\mathrm{SOR}_1, \mathrm{SOR}_2)$ and the five discrete variables: Ss, Ou_1, Ou_2, Ps and Sc.

In addition, in order to examine the influence of skull position on the measured morphological variables, four skulls were analyzed, each in six different positions: 0° (normal position), 20°, 15°, 10°, 5° dorsal flexion, and 10° ventral flexion. Position 0° refers to how the skull is oriented in the Frankfurt horizontal plane, the skull base is projected in the middle of the orbits, and symmetry is obtained (16). The focus-film distance ranged from 80 to 120 cm.

Statistical Analysis

The F-test was applied to check variance equality. Pearson's correlation coefficients were evaluated between variables characterizing frontal sinus patterns. For comparisons between groups, Fisher's exact test and the χ^2 test were performed when appropriate. According to the results of literature (7,16), measurements of the frontal sinus area were normally distributed, and the bivariate variable $\mathrm{SOR} = (\mathrm{SOR}_1, \mathrm{SOR}_2)$ was also assumed a bivariate normal random variable. Statistical analysis was carried out using the S-PLUS$^{®}$ program (release 6.1, for Windows, Professional Edition). A probability value less than 0.05 was considered significant.

TABLE 6—*Absence of Frontal Sinus in our samples.*

		Absence of Frontal Sinus			
			Unilateral		
Sex	n	Bilateral	Left	Right	Total
Male	41	6 (14.6%)	0 (0%)	3 (7.3%)	3 (7.3%)
Female	57	4 (7.0%)	5 (8.8%)	0 (0%)	5 (8.8%)

Results

The number of absent frontal sinuses in our sample is listed in Table 6. The overall frequency of bilateral absence of the frontal sinus was 10%; 15% for females and 7% for males. This difference was not statistically significant ($p = 0.31$). The relative frequency of the unilateral absence of the frontal sinus was 4%.

For quantitative assessment of potential error in identification techniques based on frontal sinus patterns, we examined the influence of skull position on the measured parameters.

The effect of changes in the position of the four skulls on the measurements of SOR = (SOR$_1$, SOR$_2$) was low compared with their inter-individual variability. Their observed intra-individual standard deviation was not greater than $s_{\max} = 0.048$ and their correlation coefficients were not lower than $r_{\min} = 0.79$. The F-test on the variances of SOR$_1$ and SOR$_2$ indicated that they were not significantly different ($p = 0.224$). Hence, we assumed that the intra-individual variability of SOR was a bivariate normal random variable, with expected values m$_1$ and m$_2$ for SOR$_1$ and SOR$_2$ respectively (their values depended on the skull in question), an identical standard deviation $s_1 = s_2 = s_{\max}$ for both SOR$_1$ and SOR$_2$ and a correlation coefficient of $r = r_{\min}$. As regards skull rotation, SOR$_1$ and SOR$_2$ values decreased when the skull's position was changed from dorsal flexion through normal position to ventral flexion.

Expected values of SOR$_1$ and SOR$_2$ for males were greater than those for females, but the differences of expected values between sexes were not statistically significant ($p = 0.24$).

In accordance with others (7), all the examined skulls showed bilateral asymmetry of frontal sinuses. The distribution of the asymmetry index was not significantly different between males and females ($p = 0.203$). In particular, the relative frequency of the unilateral absence of frontal sinus was 7% for females and 2% for males. Differences in the frequency distributions of upper border sinuses in males and females were not significant either for the left ($p = 0.22$) or right side ($p = 0.90$). Lastly, the χ^2 test did not show any significant differences between males and females with regard to the presence or absence of partial septa or supraorbital cells.

It is remarkable that the relative frequency of bilateral septa in men was far lower (7%) than in women. Even more meaningful was the low percentage of supraorbital cells in both sexes (2% for females, 4% for males).

Although by combining the various class numbers of each classification item, the Yoshino code permits more than 20,000 possible combinations, the probability that two different individuals have an identical code is higher than 1:20,000. This is because there are significant correlations between the seven characters (Table 7).

In fact, on four occasions we found a pair of X-rays which belonged to two different individuals who had the same code number. In addition, the frontal sinus patterns of a set of three individuals could be expressed by the same code numbers.

On the contrary, when the frontal sinus pattern of a given person in our sample was classified according to the bivariate continuous variable SOR = (SOR$_1$, SOR$_2$) and the five discrete variables: Ss, Ou$_1$, Ou$_2$, Ps and Sc, we found that each individual was characterized by a unique frontal sinus pattern.

TABLE 7—*Correlations among seven classification items used in Yoshino's method (Fs = frontal sinus size; Ba = bilateral asymmetry; Ss = superiority of side; Ou_1, Ou_2 = outline of upper border (left, right); Ps = partial septa; Sc = supraorbital cells).*

	Fs	Ba	Ss	Ou$_1$	Ou$_2$	Ps	Sc
Fs	1						
Ba	0.243	1					
Ss	0.436	0.524	1				
Ou$_1$	0.716	0.114	0.170	1			
Ou$_2$	0.683	0.212	0.356	0.564	1		
Ps	0.444	0.009	0.156	0.456	0.522	1	
Sc	0.270	0.137	0.044	0.369	0.444	0.103	1

In the attempt to estimate the probability of misidentification, we characterized the inter-individual SOR distribution by the sample estimated expected value ($\mu_1 = 0.458$) and standard deviation ($\sigma_1 = 0.218$) of SOR$_1$, the expected value ($\mu_2 = 0.463$) and standard deviation ($\sigma_2 = 0.217$) of SOR$_2$, and their correlation coefficient $\rho = 0.349$. Then we estimated the probability of potential error from the viewpoint of identifying individuals using SOR variables. Since SOR values are quantitative continuous characteristics of sinuses and may vary according to skull position at X-ray, we could not conclude that one and the same skull always showed an identical SOR = (SOR$_1$, SOR$_2$). Therefore, given one image of the frontal sinuses with SOR = (m_1, m_2) and fixing the probability, α, that another image of the same skull in a different position was not recognized as belonging to the same individual (α-error), we assumed that every image might come from the same individual if its SOR values fell within the ellipse of equal probabilities, G$_{1-\alpha}$(($1-\alpha$) confidence region):

$$(x_1 - m_1)^2 - 2r(x_1 - m_1)(x_2 - m_2) + (x_2 - m_2)^2 = \sigma^2 d^2$$

where $\sigma = s_{\max}$ and $d^2 = -2(1-r)^2\, ln(1-\alpha)$.

For a given skull with SOR = (m_1, m_2), the probability, ψ, that, given one image of another different skull, its SOR values fell within the interior of G$_{1-\alpha}$, was:

$$\psi = \int_{G_{1-\alpha}} p(x, y)\, dy dx$$

where $p(x, y)$ is the bivariate normal density of SOR distribution. For example, if we assume $\alpha = 0.20$ for a skull with SOR = (0.344, 1.280), it is not difficult to calculate the value of $\psi = 0.0001$.

According to this definition, the probability, β, that two different skulls are erroneously positively identified (β-error) can be calculated as the probability that they have the same values of Ss, Ou$_1$, Ou$_2$, Ps, and Sc, given that they have the same SOR value multiplied by the probability that they have the same SOR value.

Taking into account that only seven out of 98 analyzed skulls showed the same values of superiority of size, outline of the upper border (left, right), partial septa and supraorbital cells, and that the previous parameters yielded $\psi \le \psi_{\max} = 10^{-4}$, we estimated that the probability of the potential error of positive identification, β, was less than 7 10^{-6}.

Discussion

Frontal sinus patterns as sufficiently reliable indexes from the viewpoint of identifying individuals has recently been restated. The use of frontal sinus radiographs in identifying human skeletal remains is now an increasingly applied and accepted technique in forensic anthropology. In particular, the low frequency of frontal sinus aplasia may be considered a highly significant morphological characteristic for the positive identification of an individual.

One of the most widespread classification systems, that of Yoshino et al., involves formulation of the frontal sinus pattern of a given person as a code number, based on seven morphological items, and divides frontal sinus patterns into more than 20,000 possible combinations. Nevertheless, significant correlations among the code items greatly increase the probability that two individuals may have similar frontal sinus patterns, and therefore also that they are assigned identical code numbers.

To improve the performance of Yoshino's method, we replaced frontal sinus size and bilateral asymmetry by SOR_1 and SOR_2, and the frontal sinus pattern of a given person was classified according to these seven items: $SOR = (SOR_1, SOR_2)$ and the five discrete variables Ss, Ou_1, Ou_2, Ps and Sc. We did not include bilateral symmetry in the measured variables, since it is functionally dependent on SOR_1 and SOR_2 and therefore does not add information concerning skull identification.

One of the main aims of this research was to estimate the probability of potential error when using frontal sinus patterns in identification, even in circumstances where antemortem and postmortem images are made in different conditions, such as dorsal or ventral flexion of the skull. In order to evaluate our method of personal identification by frontal sinus pattern from the standpoint of degree of probability of misclassification, we assumed that SOR was a bivariate normal random variable. In this case, we had to take into account two possible errors: α) two X-ray images of the same skull in different positions are not recognized as belonging to the same individual (false negative identification); β) two X-ray images of different skulls are identified as belonging to the same individual (false positive identification).

False negative identification, α, is mainly due to the different skull position with respect to the X-ray beam. Since measurements concerning the frontal sinus area revealed high intra-individual variability, we replaced this morphological item by SOR, which showed a lower intra-individual coefficient of variance in different skull positions.

The probability of false positive identification, β, was evaluated using a bivariate normal distribution, and its unknown parameters (expected values, variances, correlation coefficients) were estimated from sample data. Hence, the greater the sample size, the more reliable the estimate of the probability of false positive identification.

The estimate of probability β in our example was obtained using a PC computer program written in S language (obtainable upon request from the first author).

It should be mentioned that SOR distribution, like many morphological characteristics, may vary according to the ancestry of the individual, whereas it does not seem to be related with sex.

The present research, carried out on 98 skulls, reveals the usefulness of frontal sinus patterns in the field of personal identification, also taking into account that our adjustments significantly decreased probability of misidentification of unknown skeletal remains.

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