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PAPER

PHYSICAL ANTROPOLOGY

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Personal Identification Using the Frontal Sinus*

ABSTRACT: The frontal sinuses are known to be unique to each individual; however, no one has tested the independence of the frontal sinus traits to see if probability analysis through trait combination is a viable method of identifying an individual using the frontal sinuses. This research examines the feasibility of probability trait combination, based on criteria recommended in the literature, and examines two other methods of identification using the frontal sinuses: discrete trait combinations and superimposition pattern matching. This research finds that most sinus traits are dependent upon one another and thus cannot be used in probability combinations. When looking at traits that are independent, this research finds that metric methods are too fraught with potential errors to be useful. Discrete trait combinations do not have a high enough discriminating power to be useful. Only superimposition pattern matching is an effective method of identifying an individual using the frontal sinuses.

KEYWORDS: forensic science, forensic anthropology, frontal sinus, identification, individualization, trait combinations, pattern matching

Radiographs have been used to identify unknown human remains since the early 1900's, and numerous skeletal traits have been examined to assist in this process. Particular attention has been paid to the skull, where several structures have the potential to positively identify an individual, including: the dentition, cranial suture patterns, mastoid pneumatic air cells, the sella turcica area of the sphenoid, and the frontal sinuses. Within the scientific literature, the frontal sinuses are generally accepted as unique to each individual. Despite numerous studies, including comparisons of twins, no two individuals have ever been shown to exhibit the same frontal sinus pattern. Still, Christensen (1) notes there are no standardized measurements of the sinuses, nor known error rates of the technique. These shortcomings render findings from the frontal sinuses inadmissible in a court of law as per the Daubert (2) ruling in the United States, and the Mohan (3) ruling in Canada.

According to the Mohan (3) ruling in Canada, judges must consider four factors when ruling on the admissibility of evidence:

- Relevance.
- Necessity in assisting the trier of fact.
- Absence of any exclusionary rule.
- Qualifications of the expert.

The Daubert guidelines (2) for determining whether evidence is admissible in the United States are more specific, giving judges a precise means of evaluating scientific testimony:

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

Rogers and Allard (4) note that the U.S. and Canadian legal systems are finding the Daubert (2) guidelines increasingly important when deciding on the admissibility of expert testimony. The Daubert Tracker (5) shows that, to date, no physical anthropological testimony has been deemed inadmissible under the Daubert (2) guidelines. Of the 39 anthropological cases challenged under the Daubert (2) ruling, only 11 were deemed to have inadmissible testimony. None of those 11 involved physical anthropological testimony; however, there are no frontal sinus cases listed on the Tracker (5) and, as per Christensen (1), the lack of a standardized technique and known error rates would likely present a problem.

The purpose of this research is to develop a standardized approach to identification using the frontal sinuses that complies with the criteria outlined in Daubert (2) for admissibility of scientific evidence. Three separate methodologies are explored: combined probabilities of metric traits, combined probabilities of discrete traits, and superimposition pattern matching.

"The frontal sinus is a paired, irregularly shaped, pneumatized cavity located in the frontal bone deep to the superciliary arch" ([6], p. 9). The sinuses develop by age 2 years (7) and are visible on X-ray around age 5 years (8). The sinuses grow slowly until puberty, then rapidly until completing their growth at approximately age 20 years (7). Since changes in the adult sinuses are rare and the sinuses remain generally stable throughout life (9), the age at which the antemortem radiograph was taken does not matter (10), providing the individual was at least 20 years old. One must

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be cautious, however, in dismissing the effects of age as the walls of the sinus can resorb with old age, making the sinuses appear larger later in life (11). The only other factors that can modify the normal sinus are trauma, surgery, and pathology. As these factors often result in X-rays for diagnostic purposes, these changes actually help the individualization process as they become documented deviations from normal anatomy (8).

While the skull has numerous individualizing traits that are visible on X-ray, only about 5% of all X-rays are of the head and neck area (12). Despite this limitation, the frontal sinuses have proven useful in forensic identification, particularly when antemortem dental records are not available, or in cases where the teeth and/or mandible are missing postmortem. The first case of identification using the frontal sinuses was performed by Culbert and Law in 1925, and published in 1927 (13). Following that, Atkins and Potsaid (14), Murphy and Gantner (15), Ubelaker (16), Jablonski and Shum (17), Marlin and colleagues (18), Reichs and Dorion (19), Haglund and Fligner (20), Owsley (21), Quatrehomme and colleagues (22), Angyal and Derczy (10), and Phrabhakaran and colleagues (23) have all published cases in which positive identification was established using the frontal sinuses. In all but one of these cases (Reichs and Dorion [19]), positive identification was achieved by a morphological X-ray comparison, essentially a superimposition match of antemortem and postmortem X-rays. Reichs and Dorion (19) achieved a positive identification through measurement of traits.

The significance of the frontal sinuses in forensic individual identification lies in their unique pattern. The acceptance within the literature that no two individuals have the same sinus pattern is so strong that some scholars (18,23) no longer cite such statements. Asherson (24) determined that even monozygotic twins present different sinus patterns. Published case studies using frontal sinuses to establish positive identification almost always involve superimposition pattern matching of ante- and postmortem X-rays. Despite this fact, the majority of research on the frontal sinuses has focused upon metric analysis. Kirk and colleagues (8) and Kullman and colleagues (25) provide the only empirical research that uses pattern matching and both found it to be almost 100% effective.

More recently, Christensen (26) attempted to create a standardized method for comparing frontal sinus patterns using Elliptic Fourier analysis (EFA). Although her results support the individuality of the frontal sinuses, Christensen notes that the technique is cumbersome and requires much time and many resources. She recommends that it only be used in cases where there is a high likelihood of the results going to trial and states that it is otherwise too complicated. A simpler, more cost-efficient technique is needed so that the forensic anthropologist can obtain accurate results from a standardized technique without having to guess whether or not the case may end up in court.

Although most researchers have focused on a combined probability approach to metric trait measurements, the assumption of independence of individual sinus traits necessary to perform such analysis has not been tested. The present research addresses this oversight through the examination of all aspects of the frontal sinuses, utilizing basic tools and simple measurements, and performing statistical analysis to determine the independence of frontal sinus traits. Combinations of independent traits are examined for their ability to individualize. Discrete traits are then examined for their usefulness in identifying an individual from their frontal sinus. The utility of superimposition pattern matching as a method of positive identification is also considered in light of the Daubert (2) and Mohan (3) criteria.

Materials and Methods

This research was conducted in several stages using X-ray films donated to the University of Toronto at Mississauga by a local hospital for research purposes. All personal information was removed from the images before research was undertaken. The total sample size was 116 individuals, selected because they had at least one anterio-posterior skull X-ray in their file. Individuals with no frontal sinuses were excluded from the sample ($n = 0$). No further screening was carried out for age, trauma, or any other factors as the more diverse the sample, the more realistic it is. One hundred of these individuals were utilized in the first stage of the research. The remaining 16 were set aside as test cases as these individuals had duplicate anterio-posterior cranial X-rays.

The first stage of analysis involved measuring all possible variables of the frontal sinuses to determine the interdependence of the traits. The list of traits was compiled and extrapolated from Cryer (27), Schuller (7), Asherson (24), and Hanson and Owsley (28). In keeping with the general technique for taking measurements of the frontal sinus, a baseline was drawn across the superior margin of the orbits (29). A tangent line was drawn at 90° to the baseline, segmenting the sinus area into quadrants. The location of the tangent line was determined by drawing a vertical line at the medial most point of each orbit (at right angles to the baseline), and measuring the distance between the two vertical orbit lines, marking the central point of that distance (Fig. 1, point X).

The baseline and the tangent line established the provenience for the measurements (Table 1). All measurements were taken using a clear plastic ruler, except where sliding calipers are stated.

The term "septum" denotes the margin between the two main sinus cavities, as it continues from the nasal septum up through the sinuses. The side scored is the anatomical side (as denoted by the tangent line) on which the proximal end of the septum line ends. (In Fig. 1, the septum begins more or less centrally, but curves to the right as it continues up into the sinuses, dividing the cavities. This is scored as "right.") Where the sinus cavities are not touching, the septum is considered to be the dividing line between the two cavities, the line is just thicker. Therefore, the septum is scored as "belonging" to the side containing the majority of the septum line. Similarly, if only one side has a cavity, there is more of the septum on the side with no cavity.

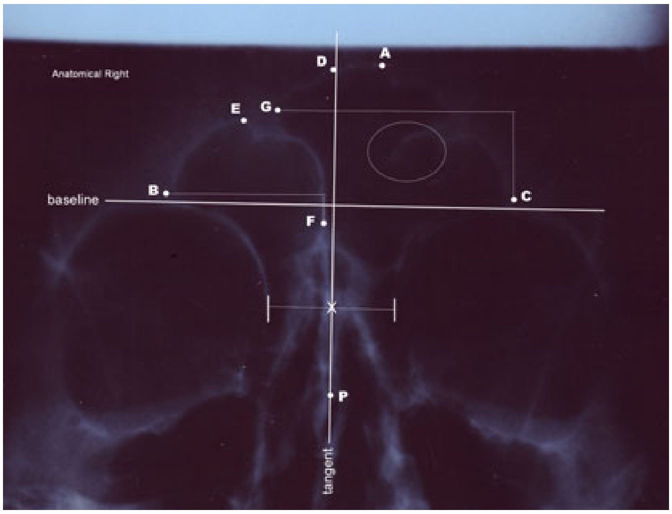

FIG. 1—*Frontal sinus measurement points.*

TABLE 1—*List of traits.*

Trait Number	General Sinus Traits
1	Deviation of septum to either side of tangential line (L/R)
2	Number of complete sinus cavities
3	Number of partial sinus lines
4	Maximum overall height above baseline (Baseline-A)
5	Maximum overall width (B–C)
Left side	
6	Number of complete sinus cavities left of septum
7	Number of partial sinus lines in main cavity
8	Number of scalloped arcades on main cavity
9	Maximum height of quadrant above baseline (Baseline-A)
10	Maximum height of main cavity above baseline (Baseline-A)
11	Maximum width of main cavity from tangent line (Tangent-C)
12	Maximum width of main cavity (C–G)
13	Distance from highest point of quadrant to most lateral point of quadrant (A–C) (Sliding Calipers)
14	Distance from highest point of main cavity to most lateral point of main cavity (A–C) (Sliding Calipers)
Right side	
15	Number of complete sinus cavities right of septum
16	Number of partial sinus lines in main cavity
17	Number of scalloped arcades on main cavity
18	Maximum height of quadrant above baseline (Baseline-D)
19	Maximum height of main cavity above baseline (Baseline-E)
20	Maximum width of main cavity from tangent line (Tangent-B)
21	Maximum width of main cavity (B–F)
22	Distance from highest point of quadrant to most lateral point of quadrant (B–D) (Sliding Calipers)
23	Distance from highest point of main cavity to most lateral point of main cavity (B–E) (Sliding Calipers)
Third and subsequent cavities	
24	Number of partial sinus lines in cavity
25	Number of scalloped arcades on cavity
26	Maximum height of cavity above baseline
27	Maximum width of cavity from tangent line
28	Maximum width of cavity
29	Distance from highest point of cavity to most lateral point of cavity (Sliding Calipers)

The main left and right cavities are located immediately next to the septum on each respective side. If one cavity appears to sit in the middle of the tangent, its side can be determined by noting to which side the septum deviates (look for a continuation up from the nasal septum), and, secondarily, which quadrant contains most of the cavity's surface area.

A partial sinus line is defined as any line 1 mm or longer extending from the border of the cavity into the cavity area, but not completely dissecting the cavity into two cells (see area enclosed by dashed oval in Fig. 1). Note that it is the number of *lines* that is recorded, not the number of partial cavities.

A scalloped arcade occurs any time the edge of a cavity arcs inward, then back out again; the change of direction (continuity) of the edge marks the end of one scallop and the beginning of another. Thus, a straight line can be part of a scallop, or, where it crosses the baseline, it is counted as a whole scallop. (In Fig. 1, the left cavity has six scallops and the right cavity has three.) Scallops are scored as any complete or partial scallop above or on the baseline, including those that occur as part of the septum. If the cavity does not cross above the baseline, only the main arc(s) projecting towards the baseline are counted.

The quadrant is the area defined by the tangent line and the baseline. As long as the cavity crosses the baseline, all measurements are taken for the upper two quadrants; however, when a cavity does not project above the baseline, measurements can still be made for the lower quadrant, but the height measurements are recorded as negative. In addition, when there is only one cavity, but it crosses the tangent line into the opposite quadrant, quadrant measurements are taken for the side that the cavity crosses into. All width measurements are measured parallel to the baseline (see Fig. 1 points C–G and B–F).

Finally, utilizing X-rays as the imaging technology, a three-dimensional structure is collapsed, depicted, and measured on a two-dimensional plane (26). Thus, the sinus cavities may appear to overlap each other.

Statistical Package for the Social Sciences (SPSS) was used to conduct Chi-square analysis of all the variables to determine their interdependence. Frequencies of each trait were established from the total sample of 100 radiographs to evaluate each trait's uniqueness and for use in calculating probabilities of obtaining combinations of traits in a single individual.

The second stage of research examined combinations of traits that were found to be independent of each other in the first stage of analysis. Using the frequency data for individual traits and probability theory, the probabilities of obtaining each combination of independent variables was calculated. The most unique combination was selected to form the basis of this stage of analysis. As most of the resulting traits are metric, this method is referred to as the "metric method." Inter- and intra-observer error tests of the metric method were also performed, followed by a blind test to ascertain the usefulness of the method in a case scenario.

The third research stage converted all possible metric traits into discrete traits in an effort to reduce the impact of image angle, film exposure, and possible effects of parallax on the scoring of traits. The probability for each combination *prior* to the discrete conversion was reviewed to determine which combination(s) would produce the most discriminating results. The variables used and the type of conversion is as follows:

The fourth and final stage of research was a superimposition test. Sixteen "duplicated" X-rays (simulated as postmortem) were compared with the dataset of 113 (simulated antemortem) for an exact pattern match. (Note that the duplicate X-rays were not an exact copy of the original; rather, the individual had more than one anterio-posterior radiograph taken of their skull. In many cases, there are subtle differences between the two. Fourteen of the 16 postmortem X-rays had matches within the dataset and two of the 16 did not, but were included anyway for test purposes. The postmortem X-rays were individually placed on a lightbox and visually compared with each of the 113 X-rays in the antemortem dataset. Possible matches were then laid atop each other on the lightbox for a closer inspection. A match was established when a visual inspection deemed the frontal sinuses of both the antemortem and postmortem X-rays were identical in every way—shape, size, contours, partial sinus lines, etc. When a match was found, the identifying number was noted and the X-ray was returned to the dataset so that all of the postmortem X-rays were compared with all 113 individuals in the dataset. An inter-observer error test was conducted using two additional researchers, one with an undergraduate degree in physical anthropology and the other a Ph.D. candidate in forensic anthropology. Thus, both are familiar with skeletal anatomy and have some experience interpreting radiographs.

Results

The raw data from the stage one measurements were entered into SPSS for statistical analysis. Cross tabulation and chi-square tests analyzed the 507 possible combinations of two traits. Three hundred and twenty-one combinations of two traits were found to be co-dependent and thus unsuitable for probability analysis. The combined probabilities of the remaining 185 combinations of two were not discriminatory enough for individualization. Seventy-four combinations of three and one combination of four independent traits were found. Their combined probabilities were evaluated and the traits were tested for intra- and inter-observer errors. The error rates were too high for the combined traits to be used effectively. For the purpose of demonstrating the difficulties of implementing a probabilistic-based method of frontal sinus identification utilizing the 23 traits defined in this project, the key results and examples are provided below.

For stage two, 74 possible combinations of three independent traits were found. Probability values for the most common and least common expression of each trait were calculated for each combination based upon the frequencies established for each variable. One combination of four independent traits was found and its most common and least common categories were also calculated. Table 2 is a summary of each trait's most and least common expression and corresponding probability value.

The most common combination involved traits 3, 6, and 15 (Table 1) and yielded a maximum probability of 0.317856. This means that three out of every 10 people manifest the most common result for each of these three traits. The least common trait expression for the same combination of traits yields a probability of 0.000018, or approximately two out of every 100,000 people. The combination of independent traits providing the lowest probability value involves variables 5, 6, 12, and 17. Utilizing each trait's most common result yields a probability value of 0.0007, or seven out of every 10,000 people, and the least common results produce a value of 0.00000001, or one out of every 100 million people. Thus, these four variables provide the most discriminating probabilities for individualization using the frontal sinus.

Intra- and inter-observer error tests were conducted on the four variables and the results were analyzed using nonparametric Mann–Whitney and two-sample Kolmogorov–Smirnov tests. In the intra-observer error tests, no statistically significant difference was found between the two groups. In the inter-observer error test, there was a statistically significant difference on variable 17 (number of scalloped arcades on the main cavity on the right side) when using the Mann–Whitney test; however, this variable was not statistically significant with the Kolmogorov–Smirnov test. The other three variables were not significantly different in either test.

A blind test of this method of matching an individual based on variables 5, 6, 12, and 17 was conducted. The test involved taking measurements from 15 X-rays, and then attempting to match those measurements to the original dataset of 113 individuals. Two of the 15 X-rays did not have a real match in the dataset. This test was first conducted with a margin of error of ±2 mm and ±1 scallop. With these parameters only four of the 15 duplicates were correctly matched, which included the two for which there was no real match; two were incorrectly matched, one was matched both to its correct counterpart and an incorrect counterpart, and eight could not be matched at all. Thus, the success rate is a mere 27%.

When the margin of error was widened to ±5 mm and ±2 scallops, only two X-rays were correctly identified (one of which did not have a real match). Six duplicate X-rays were able to be matched to their correct counterpart, but were also matched to at least one (and in one case, nine) incorrect X-rays. The remaining seven test X-rays were unable to be correctly matched with these parameters, and in most cases they found false matches. These wider parameters provide a 13% success rate of matching the duplicate X-ray to its correct counterpart and no other.

In the third stage of this research, 11 of the 29 variables were converted into discrete traits (Table 3). Sixteen combinations of three independent traits could be produced from these 11 variables. Of the 16 groups, four combinations produced a probability of 0.004 (or four people out of every thousand) with their most common categories *before* being converted to morphological traits; the next most discriminating result gave a probability of 0.016. The

TABLE 2—*Most and least common expression of each trait and its probability.*

Trait Number	Most Common Expression	*p* (Most Common Expression)	Least Common Expression	*p* (Least Common Expression)
v1	Right	0.57	None	0.07
v2	2	0.75	4	0.02
v3	0	0.42	5	0.03
v4	19 mm	0.09	Multiple entries	0.01
v5	62 mm	0.06	Multiple entries	0.01
v6	1	0.86	3	0.01
v7	0	0.54	Multiple entries	0.01
v8	3	0.22	Multiple entries	0.01
v9	21 mm	0.09	Multiple entries	0.01
v10	Multiple entries	0.09	Multiple entries	0.01
v11	31 mm	0.07	Multiple entries	0.01
v12	32 mm	0.07	Multiple entries	0.01
v13	Multiple entries	0.05	Multiple entries	0.01
v14	Multiple entries	0.05	Multiple entries	0.01
v15	1	0.88	Multiple entries	0.06
v16	0	0.60	No cavity	0.06
v17	2	0.20	10	0.01
v18	20 mm	0.08	Multiple entries	0.01
v19	14 mm	0.07	Multiple entries	0.01
v20	Multiple entries	0.05	Multiple entries	0.01
v21	23 mm	0.06	Multiple entries	0.01
v22	23 mm	0.07	Multiple entries	0.01
v23	No cavity	0.06	Multiple entries	0.01

(''Multiple entries'' is when more than one expression of the trait has the same frequency and probability. The *p*-value columns are the probabilities of each expression.)

TABLE 3—*List of variables converted to morphological traits.*

Trait Number	General Sinus Traits
1	Deviation of septum to either side of tangential line → Remained as ''Left'' or ''Right''
3	Number of partial sinus lines → Converted to ''Present'' or ''Absent''
4	Maximum overall height above baseline (Baseline-A) → Converted to ''Above'' or ''Below'' with below including 0 mm or ''on the baseline''
Left side	
6	Number of complete sinus cavities left of septum → Converted to ''Present'' or ''Absent''
7	Number of partial sinus lines in main cavity → Converted to ''Present'' or ''Absent''
9	Maximum height of quadrant above baseline (Baseline-A) → Converted to ''Above'' or ''Below'' with below including 0 mm or ''on the baseline''
10	Maximum height of main cavity above baseline (Baseline-A) → Converted to ''Above'' or ''Below'' with below including 0 mm or ''on the baseline''
Right side	
15	Number of complete sinus cavities right of septum → Converted to ''Present'' or ''Absent''
16	Number of partial sinus lines in main cavity → Converted to ''Present'' or ''Absent''
18	Maximum height of quadrant above baseline (Baseline-D) → Converted to ''Above'' or ''Below'' with below including 0 mm or ''on the baseline''
19	Maximum height of main cavity above baseline (Baseline-E) → Converted to ''Above'' or ''Below'' with below including 0 mm or ''on the baseline''

variables used in the top four combinations of three were converted to morphological traits using SPSS and the frequencies of each were calculated. Probabilities of exhibiting the top four trait combinations were calculated from the frequencies, producing results of 0.5 each (Table 4). Therefore, half of all people will exhibit the most common expression of these trait combinations.

In the fourth stage of research, 16 duplicate X-rays were compared with the dataset of 113 for exact pattern matches. All 16 were correctly identified, including the two X-rays that did not have a match in the dataset (they were correctly identified as having "no match"). This method was retested for intra-observer error and found to be 100% reliable. The inter-observer error test was similarly successful—researchers were able to correctly match all 16 X-rays.

Discussion

In attempting to establish a standardized method for utilizing the frontal sinuses as a form of individualizing identification, most previous research has focused upon taking multiple measurements of the sinuses and combining the probabilities of each measurement for analysis (6,9,19,25,30). This approach has one inherent flaw: no one has tested the traits to establish their independence from one another. The first stage of the current study assessed the interdependence of 23 traits of the frontal sinuses. Many of the traits were found to be dependent upon one another and thus unsuitable for combined probability analysis. These findings undermine much of the previous research on positive identification techniques that utilize the frontal sinuses.

In the second stage of this research, the first 23 traits were examined to find independent trait combinations. The variables used were those that pertained to the overall measurements, and those specific to the main sinus cavities on each side of the septum. Eighty-five percent of the population manifested up to two sinus cavities, and only 15% present with three or more. Given these results, it was decided to exclude variables pertaining to the third and subsequent cavities. If an individual presented with a third cavity, the traits of that cavity were considered independent of all other traits. (The exceptions to this rule are the following combinations: the side of the third cavity cannot be combined with the number of cavities on either the left or right side, nor can the number of scalloped arcades on the third cavity be combined with either the total number of partial cavities, or the number of scalloped arcades on the left side.) Chi-square values for individuals with four cavities were unavailable because only one person in the dataset presented with this combination.

An examination of the trait combinations reveals that even when one is working with the most common results, there are many combinations that will provide a probability value in the thousands, (i.e., X out of every thousand people have that particular combination of traits). This is statistically significant to forensic anthropologists who are attempting to perform an individual identification using the frontal sinuses. The target population pool to which the forensic anthropologist compares an unknown individual is much smaller than one may realize. When human remains are found, the forensic anthropologist compiles a biological profile of the individual. This profile is applied to the missing persons' database for that state, province, or territory. This eliminates many, if not most, of the possible matches. Thus, a result of X out of every thousand for the most common trait combination is precise enough to compare to the missing persons fitting the biological profile for elimination and identification. Unlike DNA analysis, which attempts to match one unknown sample to the total population to find a perpetrator, frontal sinus analysis only has to compare to the population of missing persons who match the biological profile; probabilities do not have to eliminate millions of other possibilities, just a few hundred.

TABLE 4—*Combinations of independent discrete traits and their most common probability values.*

v1	p(v1)	v2	p(v2)	v3	p(v3)	p(v1 × v2 × v3)
6	0.96	16	0.6	18	0.92	0.52992
4	0.97	6	0.96	16	0.6	0.55872
6	0.96	9	0.94	16	0.6	0.54144
6	0.96	10	0.91	16	0.6	0.52416

(Columns headed "v#" are the trait numbers as per Table 2. The p value columns are the probabilities of each expression.)

The most useful trait combination for the purpose of individualization is the one which produces the lowest probability result using the most common expression of the trait. The most common expressions of each trait are those that are most likely to be found on any individual. When these traits are combined with a low probability, it provides a higher discriminating power. For example, this research found the combination that utilizes four independent traits has the lowest probability. Those traits are: maximum overall width (v5) ($p = 0.06$), number of cavities left of the septum (v6) ($p = 0.86$), maximum width of the main cavity left of the septum (v12) ($p = 0.07$), and number of scalloped arcades on the main right cavity (v17) ($p = 0.2$). When the probabilities for the most common expression for each of these traits are combined, the result shows that 7/10,000 people manifest that combination. This is more than adequate to compare to a pool of possible matches in the missing persons' database.

The intra- and inter-observer error tests were analyzed using both the Mann–Whitney *U*-test and the Kolmogorov–Smirnov test. Although these tests found that there was no significant difference between the test data and the original, the blind test found that this method of metrically measuring the sinuses is unsuitable for positive identification. The slightest change in the angle or exposure of the duplicate or postmortem X-ray can result in a mismatch or no match at all. In some cases, the margin of error required to obtain a match also incorporated up to nine mismatches, giving a total of 10 possible matches out of a dataset of 113. These results are not discriminating enough for forensic anthropologists to be able to use this technique to individualize someone and present the findings in a court of law. As was noted by Kirk and colleagues (8), metric matching does not work because of the high error rates.

Once it was determined that positive identification by metric measurements was unsuitable, a discrete approach was attempted. Unfortunately, due to the "presence/absence" nature of the scoring of these traits, the probability values of the combinations were found to have no discriminating power. A probability of 0.5, or five people out of every 10, is not strong enough to individualize a person and will not hold up in court.

The final method of personal identification using the frontal sinuses examined in this research was superimposition. Ubelaker (16) used superimposition to determine that any two individuals have at least three points of difference in their frontal sinuses. Rather than examine the differences between individuals, this research attempted to match 16 simulated postmortem X-rays to a dataset of 113 simulated antemortem X-rays. This method was found to be 100% reliable and accurate through intra- and inter-observer error tests. No extra equipment is required for this method and even observers with minimal experience with X-rays are able to correctly utilize this technique. Furthermore, unlike the metric method attempted in stages one and two of this research, subtle differences in the angle and exposure of the X-rays do not significantly influence the outcome.

One of the common guidelines in the literature regarding the matching of antemortem radiographs to postmortem radiographs involves the distance and angle at which each radiograph is taken. While researchers caution that one should always try to match the postmortem radiographic distance and angle to the antemortem, it was not until 1987 that Harris and colleagues (6) published research regarding the most appropriate way this can be accomplished. Until then, it appeared as if obtaining a postmortem radiograph at the same angle and distance to the antemortem was considered the luck of the draw. Despite these potential discrepancies in orientation, Kullman and colleagues (25) conducted a study of radiographic pattern matching using the frontal sinuses of 100 individuals and noted that while their sample contained several pairs of X-rays taken from different angles, these differences barely affected the success of their observers to match the pairs. This research confirms Kullman and colleagues' (25) findings in this matter.

The results of the fourth stage of this research show that superimposition pattern matching provides an accurate positive identification 100% of the time. Thus, superimposition pattern matching provides a probability of obtaining a correct match of 1. This data is further supported in similar research findings by Kirk and colleagues (8) and Kullman and colleagues (25). Therefore, one could give testimony in court that the technique of personal identification from the frontal sinuses using superimposition pattern matching has been tested using the scientific method, has been subjected to peer review, is 100% accurate and precise with a known error rate of zero, and is generally accepted within the scientific community, as per the Daubert (2) criteria. Further, these results can be generalized to the global community as, like fingerprints, frontal sinuses are accepted as unique to each individual and unaffected by ancestry (25).

Despite the frontal sinuses' unique nature and their use in identification since 1925, there are currently no standardized techniques for establishing an empirical match between antemortem and postmortem records. The interdependence of many frontal sinus traits has been established, refuting the findings of previous research. Although probability analysis supports the strength of metric differentiation of the frontal sinuses, testing of this method shows that it has inherently high error rates that render it unsuitable for use in an individualizing setting. Discrete traits are also useless for individualization with the frontal sinuses because of the low levels of discriminating power provided by the probability analysis. Superimposition pattern matching provides the simplest method of obtaining an individual match from the frontal sinuses with the highest levels of accuracy and precision and the lowest level of error. This method should be utilized as the standard methodology when trying to obtain an individual identification using the frontal sinuses as it meets all the Daubert (2) criteria. Only by meeting these stringent requirements can the frontal sinuses be utilized as individual identifiers in a court of law.

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