J Forensic Sci, Jan. 2005, Vol. 50, No. 1
Paper ID JFS2004145
Available online at: www.astm.org

Angi M. Christensen,[1] *Ph.D.*

Testing the Reliability of Frontal Sinuses in Positive Identification*

ABSTRACT: The use of frontal sinus radiographs in positive identification has become an increasingly applied and accepted technique among forensic anthropologists, radiologists, and pathologists. From an evidentiary standpoint, however, it is important to know whether frontal sinus radiographs are a reliable method for confirming or rejecting an identification, and standardized methods should be applied when making comparisons. The purpose of the following study is to develop an objective, standardized comparison method, and investigate the reliability of that method. Elliptic Fourier analysis (EFA) was used to assess the variation in 808 outlines of frontal sinuses by calculating likelihood ratios and posterior probabilities from EFA coefficients. Results show that using EFA coefficient comparison to estimate the probability of a correct identification is a reliable technique, and EFA comparison of frontal sinus outlines is recommended when it may be necessary to provide quantitative substantiation for a forensic identification based on these structures.

KEYWORDS: forensic science, forensic anthropology, frontal sinuses, positive identification, elliptic Fourier analysis, geometric morphometrics

The use of frontal sinus radiographs in confirming the identity of human remains of an unknown individual has a relatively long history in forensics (1). A typical comparison is usually performed as follows: a suitable antemortem radiograph is located, usually following a presumptive identification. Next, a postmortem radiograph is taken at a similar orientation and magnification as the antemortem radiograph. Finally, the two radiographs are compared visually, looking for common points or features (Fig. 1).

In the past, such identifications have been readily accepted as admissible in courts of law. However, in courtrooms today, it is exceedingly rare that an expert's opinion goes unchallenged, and recent rulings in admissibility law require more than experience, credibility and persuasion of the scientific expert.

The issues of challenged expertise and the admissibility of experts' opinions have become particularly important following the 1993 case of *Daubert v. Merrell-Dow* (2) in which the Supreme Court ruled upon the admissibility of scientific evidence in federal trials. The resulting "*Daubert* Guidelines" are intended to ensure that evidence is grounded in good science, and outline four criteria for evaluating scientific evidence to determine whether it is scientifically sound: 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; and 4. General acceptance within the relevant scientific community.

The method of identification by frontal sinus comparison appears to fulfill two of the criteria, but the remaining two may present challenges (3). There are certainly a large number of publications relating to the individual variability of frontal sinus morphology and on case studies where they have been used as a means of personal identification. There also appears to be general acceptance within the fields of forensic anthropology, pathology and radiology that the visual comparison method is sufficiently reliable.

However, while frontal sinus identification reliability is *capable* of being empirically tested, no such tests have been performed. Moreover, there is very little research aimed at quantification with the consequence that no error rate has been estimated. There are also no professional standards established for the application of the technique. Finally, the visual comparison method is largely subjective, based on the knowledge, experience or ability of the examiner.

Few may have considered these factors to be potential shortcomings until the 2002 case of *United States v. Plaza* (4) questioned the admissibility of fingerprint analysis due to the Supreme Court's original finding that the technique did not meet several of the *Daubert* guidelines. While the Court eventually allowed the fingerprint examiner's identification and opinion into evidence, this issue obviously has important implications for the potential of frontal sinus identifications to meet the *Daubert* guidelines, if challenged.

While the usefulness of comparing antemortem and postmortem frontal sinus radiographs in forensic contexts is fully and widely appreciated, more extensive research into the statistical reliability of diagnostic features used in positive identification is necessary, and more objective standards for confirming or rejecting an identification should be established. The following study was conducted with the purpose of developing an objective, standardized comparison method, and investigating the reliability of frontal sinuses in personal identification.

Materials and Methods

Sample

Frontal sinus radiographs used for this study were acquired from four sources. First, radiographs of skulls of two skeletal collections housed at the University of Tennessee Department of Anthropology were taken for this study. The William M. Bass Donated Skeletal

[1] The University of Tennessee, Department of Anthropology, Knoxville, TN.

* Presented at the 56th annual meeting of the American Academy of Forensic Sciences, Dallas, Texas February 20, 2004.

Received 28 June 2003; and in revised form 21 Dec. 2003 and 2 Sept. 2004; accepted 2 Sept. 2004; published 8 Dec. 2004.

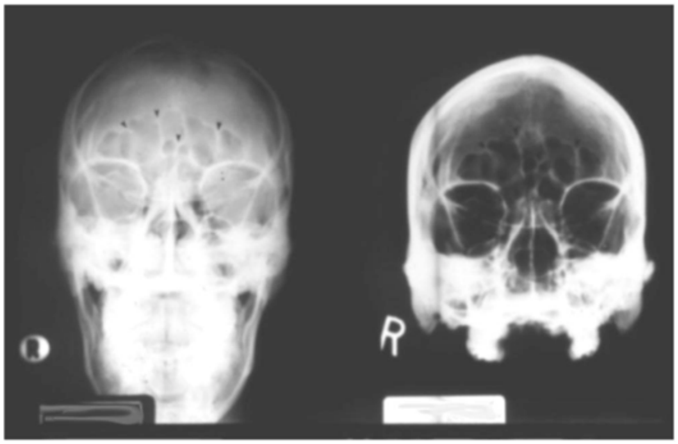

FIG. 1—*Comparison of antemortem (left) and postmortem (right) frontal sinus radiographs.*

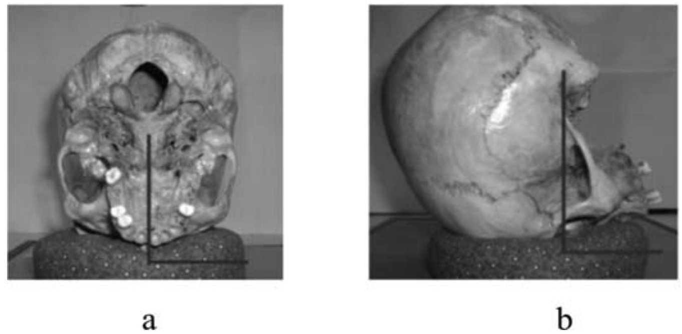

FIG. 2—*Orientation (a) along the median palatine suture, and (b) along a straight line through the superior margin of the external auditory meatus and nasion.*

Collection consists of partial and complete skeletal remains of donated individuals, 257 of which were suitable for this study by virtue of having present, complete, and undamaged frontal regions. The University of Tennessee Forensic Skeletal Collection consists of skeletons of human and non-human remains from forensic cases, 105 of which were suitable for this study. The other two sources were two sets of radiographs: 61 historic plains Arikara crania radiographed by a previous researcher, and 161 radiographs from the University of Tennessee Student Health Center taken for clinical purposes.

Radiograph Methodology

Cranial radiographs taken for this study were performed at the University of Tennessee Student Health Center with the assistance of an x-ray technician using a HoLogic HFQ Series 100 kHz High Frequency machine and Kodak T-Mat G/RA film. The settings used for this study were developed on a trial-and-error basis, and for most specimens the parameters were:

KVP (peak kilovoltage):	48–50 kV_{peak}
CM (distance from tube to film):	40 cm
MA (current in the x-ray tube):	75 mA
SEC (exposure time):	65 ms

A standardized methodology was used to orient the skulls in the following manner: The image beams traversed the skull posterior to anterior with the frontal bone nearest the film to allow minimal distortion and maximum clarity of the frontal sinus outline. The skull was placed face down on a foam/cloth doughnut with the midsagittal plane perpendicular to the x-ray film using the median palatine suture as a guide (Fig. 2*a*). Next, the skull was oriented with a straight line running through nasion and the superior border of the external auditory meatus perpendicular to the film (Fig. 2*b*). The central axis of the X-ray beam was centered on a point between the external occipital protuberance and lambda.

This subset of the total sample (those radiographs taken specifically for this study) allowed repeated access to the same crania. Consequently, duplicate radiographs could be taken, simulating antemortem and postmortem. Each duplicate was taken using the same methodology but at a different time so that the skull would have to be re-oriented and duplicates would not simply be copies.

A total of 946 radiographs were examined (584 individuals, 362 of which had duplicates). Some of the radiographs could not be used, however, either because there was no frontal sinus visible at all or because the sinus present was too small to be suitable for the method of analysis selected (see below). The resulting subsample consisted of 503 individuals, 305 of whom had duplicates radiographs (Table 1).

Obtaining Outlines, Coordinates and EFA Coefficients

Outlines for comparison were obtained by superimposing each original radiograph (Fig. 3*a*) with tracing paper, and tracing the frontal sinus outline onto the paper over a light table. Only the outermost border of each frontal sinus was traced and did not include partial or complete septations. While the upper and lateral limits of the frontal sinus are easily defined and readily discernable, the lower limit is significantly more difficult to locate on radiographs. Many researchers have recognized this problem, and as a consequence, several methods of arbitrarily delimiting the lower margin have been proposed. One widely accepted method, first proposed by Libersa and Faber (5), involves a "baseline" drawn tangential to the upper margin of the orbits (Fig. 3*b*). This method was

TABLE 1—*Sample of radiographs used.*

Sample	Total Number of Radiographs Examined	Number Not Used Due to Absent or Too Small Sinuses	Total Number of Radiographs Used in This Study
University of Tennessee Donated Skeletal Collection	257 (×2)	27 (×2)	230 (×2)
University of Tennessee Forensic Skeletal Collection	105 (×2)	30 (×2)	75 (×2)
University of Tennessee historic plains Arikara	61	9	52
University of Tennessee Student Health Center	161	15	146
Total	584	81	503 (305 of which have "antemortem" and "postmortem" duplicates)

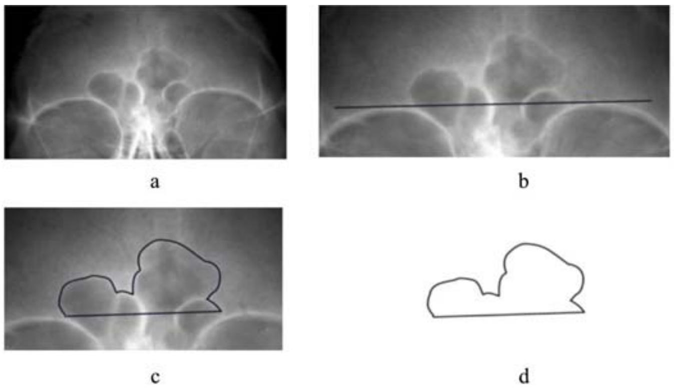

FIG. 3—*(a) Original radiograph; (b) arbitrary baseline; (c) outlined shape of interest; and (d) the final outline.*

selected for the current study because it is easy to apply and replicate, and several previous researchers have recognized it as an accepted methodology (5,6–12). The resulting outline consisted of a closed contour representing the natural lateral and superior borders of the sinus and a straight, arbitrary inferior border (Fig. 3*c*, *d*).

The traced outlines were scanned using a UMAX Astra 2400s scanner and saved in *.JPG format as black and white images with 600 dpi resolution. Next, the outlines were converted to series of Cartesian coordinates using the software package tpsDig (13). Individual images were imported into tpsDig, and the coordinate data were collected and saved into two *.tps files; one that contained the coordinates for single copies of each frontal sinus outline examined (hereafter referred to as "singles"), and a second that contained the coordinates for duplicate outlines of individuals with two frontal sinus outlines to examine ("duplicates").

The method of elliptic Fourier analysis, or EFA, (14) is a procedure that can fit a closed curve to an ordered set of data points with any desired degree of precision using an orthogonal decomposition of a curve into a sum of harmonically related ellipses. The ellipses can be combined to arbitrarily approximate a closed plane curve given enough harmonics (15).

EFA is based on separate Fourier decomposition of the first differences of the x and y-coordinates (Δx_i and Δy_i) as parametric functions of the cumulative chordal distance, t, of the points around the outline where t is scaled to go from 0 to 2π (16). The x- and y-coordinates of points along the length, t, of an outline can be represented as a sum of k harmonics using sine and cosine terms:

$$x(t) = A_0 + \sum_{k=1}^{n} (A_k \cos kt_k + B_k \sin kt_{k-1})$$

$$y(t) = C_0 + \sum_{k=1}^{n} (C_k \cos kt_k + D_k \sin kt_{k-1})$$

EFA generates four coefficients (A_k, B_k, C_k, D_k) that can be treated as a set of shape descriptors used for variables in discriminatory or other multivariate analyses (17). The coefficients of the kth harmonic of the outline's x-projection are:

$$A_k = \frac{T}{2p^2\pi^2} \sum_{k=1}^{p} \frac{\Delta x_i}{\Delta t_i} \left[\cos \frac{2\pi k t_i}{T} - \cos \frac{2\pi k t_{i-1}}{T} \right]$$

$$B_k = \frac{T}{2p^2\pi^2} \sum_{k-1}^{p} \frac{\Delta x_i}{\Delta t_i} \left[\sin \frac{2\pi k t_i}{T} - \sin \frac{2\pi k t_{i-1}}{T} \right]$$

where:

p = the number of steps around the outline
$\Delta x_i = x_i - x_{i-1}$
Δt_i = the chordal distance of the step between points $i-1$ and i
t_i = the cumulative length of such steps up to step i
$T = t_p$ = the total length of the outline contour

The coefficients for the y-projection, C_k and D_k are found in the same way using the incremental changes in the y-direction.

Elliptic Fourier coefficients were generated from the *.tps files using the software package EFAWin (18), a program that computes elliptic Fourier coefficients for an outline described by a set of x- and y-coordinates. This was done after converting the coordinates (obtained in tpsDig) to an EFAWin-compatible format using tpstoefa (19), a program that converts a directory of *.tps files with outlines into a single file for EFAWin.

Likelihood Ratios and Posterior Probabilities

The reliability of comparisons (or the uniqueness of individual outlines) was quantitatively assessed using the resulting EFA coefficients. Assertions of uniqueness should be given as the probability of a match given the correct identification versus the probability of a match from the population at large. The EFA coefficients were thus used to calculate likelihood ratios and posterior probabilities for comparisons of outline pairs.

A likelihood ratio is the probability of some evidence supposing the hypothesis is true, over the probability of the evidence supposing it is false (20). Here, the hypothesis is that two frontal sinus outlines belong to the same individual, and the likelihood ratio is the probability that the frontal sinuses match given the correct identification (i.e., its own duplicate) over the probability of a match from the population at large (i.e., the rest of the outlines):

$$\frac{P(x_2|x_1)}{P(x_2|\mu)}$$

To calculate the likelihood ratio, one first needs a parametric form for the above. Multivariate normal would be ideal, but it does not work here, because the coefficients are Laplace, not normally, distributed. The likelihood ratio is thus represented as:

$$\frac{b_s}{b_d} \exp \frac{(-|x_1 - x_2|/b_s)}{(-|x_1 - \mu|/b_d)}$$

where:

x_1 = the EFA coefficients from duplicate 1 (simulated antemortem)
x_2 = the EFA coefficients from duplicate 2 (simulated postmortem)
b_s = the variation among "singles"
b_d = the variation within "duplicates"

Likelihood ratios were calculated in R (21), and summary statistics for the ratios were calculated in Microsoft Excel (22). A likelihood ratio greater than 1 indicates evidence in favor of the hypothesis, while a ratio less than 1 is evidence against it, with 1 being neutral. Any evidence with a likelihood ratio greater than 1 is relevant from an evidentiary perspective, and the further from 1 the ratio is, the greater the probative value of the evidence (20). For simplification and ease of viewing, the resulting likelihood ratios were converted to log base-10 scale.

Posterior probabilities were calculated by dividing the likelihood ratio by the likelihood ratio plus one. The posterior probability

TABLE 2—*Log likelihood ratios.*

	Log Likelihood Ratio	
Number of Harmonics	Mean	Standard Deviation
1	1.81	1.32
5	10.09	4.96
10	16.64	9.02
15	20.02	12.88
20	21.22	16.54

TABLE 3—*Posterior probabilities.*

Number of Harmonics	Mean	Standard Deviation
1	0.88	0.23
5	0.96	0.18
10	0.94	0.22
15	0.92	0.25
20	0.90	0.29

represents the probability that the identification is correct assuming that the identification (prior to the osteological evidence) is as likely to be correct as incorrect (this assumption is discussed further later).

Results

Likelihood Ratios from EFA Coefficients

A summary of the log likelihood ratios for 1, 5, 10, 15 and 20 harmonics is shown in Table 2. A likelihood ratio of 1 would indicate that you would be equally likely to get that difference between duplicates of the same individuals as you would between different individuals. The likelihood ratios in this study are very large, and increase with increasing harmonics (although it appears asymptotic). In other words, the odds of a match given the correct identification are significantly higher than the odds of a match from the population at large. Indeed, using 20 harmonics, the odds are about $10^{21.22}$ to 1.

The posterior probabilities for 1, 5, 10, 15, and 20 harmonics are shown in Table 3. These results suggest that the probability of identifying a correct identification given a match (and using 5 harmonics) would be nearly 96%, a favorably high level of reliability. This 5 harmonic peak (and subsequent decline with larger harmonics) is likely due to the fact that more than 5 harmonics was too many, introducing "noise".

Discussion

These results quantitatively support previous notions of the individualized quality of frontal sinus outlines and their reliability in forensic identifications. However, these results provide a rather conservative estimate of reliability. The calculations presented here represent the probability of a match given the correct identification. In forensic contexts, what we are interested in is the probability that the identification is correct given that the frontal sinuses match, or, the odds in favor of a correct identification after taking other evidence into account. *Bayes' Theorem* (23) tells us how to update our knowledge by incorporating other information, called prior odds.

Prior odds, which are 1 only if the probability of a correct identification is as likely as an incorrect one, are almost always greater than 1 in forensic cases because there is already other evidence to suggest that two radiographs belong to the same individual (medical records, of course, were not selected at random from the population at large).

Assuming a prior odds of 1 thus provides only the *most conservative* estimate of a correct identification in the absence of any other information or evidence. In this study, even this conservative estimate suggests a probability of about 96%. The technique, therefore, should be considered a sufficiently reliable method for confirming or rejecting a positive identification.

Limitations of the Method

The method of comparing frontal sinus radiographs is highly dependent on the accuracy and availability of hospital and/or mortuary records; inadequate, unreliable or unavailable antemortem or postmortem data can prove a great hindrance to this identification method. Even if a record of a cranial radiograph is available for comparison, it may still fail to be applicable to identification using this technique for a number of reasons.

A subset of the population lacks radiographically demonstrable frontal sinuses, either because they are too small to be seen on radiographs, or because they are confined to the horizontal (orbital) portion of the frontal bone (24). This problem is similar to one experienced in dental identifications—those who have a dental record but who have unremarkable dentition (i.e., have no restorations, gaps, etc.) are not ideal for dental comparisons for confirming identity (25). However, given that they comprise only a small percent of the population, significant likelihood ratios may still result. If, for example, p represents the proportion of individuals without frontal sinuses (which in the sample used here was 81 out of 584 or about 14%), then the likelihood ratio for a sinus-less individual would be $1/p$, or 1/(81/584) or 7.3. Thus, even for comparisons of sinus-less individuals, likelihood ratios would be significantly greater than 1, and may still be useful in forensic comparisons.

Cases of subadults or those whose frontal sinuses have been affected by pathology or trauma also present potential applicability problems and should be considered with caution as changes in the size and shape of the frontal sinuses may have occurred (26); however, this did not appear to affect the ability to identify a match in a study by Kirk et al. (27).

One should also consider the limitations of using conventional radiography. All structures in the path of the X-ray beam appear superimposed on the image and cannot be distinguished from each other; "collapsing" three-dimensional structures into two dimensions provides only limited information on structures such as frontal sinuses (28). The method used here to investigate variability further reduces the representation of the structure to that portion located above the baseline.

One final question to consider is: Should forensic scientists bother with this method of frontal sinus-based positive identification? Given the acceptance that visual assessments have gained in the past, and the success with which they have been applied, it may be redundant or unnecessary to perform EFA on all frontal sinus comparisons in forensic contexts. A visual assessment can be performed quickly and easily, while EFA will require more time and resources, which may make it significantly less appealing. Indeed, the analyses performed here lend strong support to previous notions of the individuality of frontal sinus outlines, so in many cases visual assessments are probably justified. The EFA technique may prove particularly valuable in cases that may go to trial and therefore will likely be challenged by another expert and/or opposing council. In such cases, the results of an EFA comparison may significantly strengthen the expert's argument by demonstrating that the comparison technique meets *Daubert* guidelines in having been empirically substantiated. Perhaps the technique could be further enhanced (and made somewhat less cumbersome) by the development of a software package designed to specifically address and facilitate forensic EFA comparisons.

Conclusion

The EFA method of frontal sinus radiograph comparison can be applied objectively and quantitatively to personal identification cases. Moreover, the method was concluded to be reliable for comparing frontal sinus outlines to confirm or reject a putative identification. Based on the calculated likelihood ratios and posterior probabilities, the probability of recognizing a correct (or incorrect) identification is about 96%.

Acknowledgments

I would like to thank the following individuals, whose contributions greatly enhanced the quality of this research: Lyle Konigsberg, Richard Jantz, Kenneth Rule, Murray Marks, and Hermann Prossinger for their direction and support; Dennis Slice who was a great help in developing the protocol for the study; Cathy Graves who assisted with data collection; and Adam Sylvester who assisted with data collection and analysis. Finally, I would like to acknowledge the William M. Bass Endowment for providing financial support for the study.

References

1. Culbert WL, Law FL. Identification by comparison of roentgenograms of nasal accessory sinuses and mastoid processes. JAMA 1927;88:1634–6.
2. *Daubert v. Merrell Dow Pharmaceuticals, Inc.*, 509 U.S. 579 (1993).
3. Christensen AM. The impact of *Daubert*: implications for testimony and research in forensic anthropology (and the use of frontal sinuses in personal identification). J Forensic Sci 2004;49(3):1–4.
4. *United States of America v. Carlos Ivan Lleva Plaza, Wilfredo Martinez Acosta, and Victor Rodriguez* Cr. No. 98–362–10, 11, 12 2002.
5. Libersa C, Faber M. Etude Anatomo-radiologique du sinus frontal chez l'enfant. Lille Med 1958;3:453.
6. Brothwell DR, Molleson T, Metreweli C. Radiological aspects of normal variation in earlier skeletons: an exploratory study. In: Brothwell DR, editor. The Skeletal biology of earlier human populations. New York: Pergamon Press, 1968;149–72.
7. Buckland–Wright JC. A radiograhic examination of frontal sinuses in early British populations. Man 1970;5:512–7.
8. Hanson CL, Owsley DW. Frontal sinus size in Eskimo populations. Am J Phys Anthropol 1980;53:251–5. [PubMed]
9. Ikeda J. Interpopulation variations of the frontal sinus measurements: comparison between the Jamon and Recent Japanese population. J Anthrop Soc Nippon 1980;90 Suppl.
10. Koertvelyessy T. Relationships between the frontal sinus and climatic conditions: a skeletal approach to cold adaptation. Am J Phys Anthropol 1972;37:161–72. [PubMed]
11. Ribeiro FA. Standardized measurements of radiographic films of the frontal sinuses: an aid to identifying unknown persons. Ear Nose Throat J 2000;79:26–33. [PubMed]
12. Strek P, Kaczanowski K, Skawina A, Pitynski K, Kitlinski Z, Mrowka D, et al. The morphological evaluation of frontal sinuses in human skulls. Folia Morphol (Warsz) 1992;51:319–28. [PubMed]
13. Rohlf FJ. tpsDig version 1.07. Morphometrics at SUNY Stony Brook 1997 http://life.bio.sunysb.edu/morph/.
14. Kuhl FP, Giardina CR. Elliptic Fourier features of a closed contour. Computer Graphics and Image Processing 1982;18:236–58.
15. Ferson SF, Rohlf FJ, Koehn RK. Measuring shape variation of two-dimensional outlines. Syst Zool 1985;34:59–68.
16. Rohlf FJ. Fitting curves to outlines. In: Rohlf FJ, Bookstein FL, editors. Proceedings of the Michigan morphometrics workshop. Ann Arbor: University of Michigan Museums of Zoology, Special Publication 2, 1990.
17. Bookstein FL, Strauss RE, Humphries JM, Chernoff B, Elder RL, Smith GR. A comment upon the uses of Fourier methods in systematics. Syst Zool 1982;31:85–92.
18. Isaev M. EFAWin 1995. Morphometrics at SUNY Stony Brook. http://life.bio.sunysb.edu/morph/.
19. Page R. tpstoefa. Fourier analysis of outlines 1998 http://taxonomy.zoology.gla.ac.uk/rod/docs/fourier/fourier.html.
20. Robertson B, Vignaux GA. Interpreting evidence: evaluating forensic science in the courtroom. Chichester: John Wiley and Sons, 1995.
21. R Development Core Team. R Version 1.7.1 2003 www.r-project.org.
22. Microsoft Excel. Version 9.0.2719. Microsoft Corporation, 1999.
23. Bayes T. An essay towards solving a problem in the doctrine of chances. Philosophical Transactions of the Royal Soc of London 1763;53:370–418.
24. Shapiro R, Janzen AH. The normal skull: a roentgen study. New York: Paul B. Hoeber, Inc., 1960.
25. Adams BJ. Establishing personal identification based on specific patterns of missing, filled, and unrestored teeth. J Forensic Sci 2003;48(3):1–10.
26. Dolan KD. Paranasal sinus radiology part 1B: the frontal sinuses. Head Neck Surg 1982;4:385–400. [PubMed]
27. Kirk NJ, Wood RE, Goldstein M. Skeletal identification using the frontal sinus region: a retrospective study of 39 cases. J Forensic Sci 2002;47(2):318–23. [PubMed]
28. Spoor F, Jeffery N, Zonneveld F. Imaging skeletal growth and evolution. In: O'Higgins P, Cohn MJ, editors. Development, growth and evolution. San Diego: Academic Press, 2001;123–61.

Additional information—reprints not available from author:
Angi M. Christensen, Ph.D.
250 S. Stadium Hall
Knoxville, TN 37996