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Radiographic Human Identification Using Bones of the Hand: A Validation Study*

ABSTRACT: The 1993 Supreme Court case *Daubert v. Merrell-Dow Pharmaceuticals, Inc.* underscores the importance of validating forensic science techniques. This research examines the validity of using posterior-anterior radiographs of the hand to make positive identifications of unknown human remains. Furthermore, this study was constructed to satisfy the requirements of *Daubert's* guidelines of scientific validity by establishing a standard methodology for hand radiograph analysis, testing the technique, and noting rates of error. This validation study required twelve participant examiners from the forensic science community, working independently, to attempt to match 10 simulated postmortem radiographs of skeletonized hands to 40 simulated antemortem radiographs of fleshed cadaver hands. The overall accuracy rate of the twelve examiners was 95%, while their collective sensitivity and specificity were 95% and 92%, respectively. However, the accuracy of each examiner was related to the amount of radiological training and experience of the observer. Six Ph.D. forensic anthropologists and four experienced forensic anthropology graduate students correctly identified all the matches. Participant examiners noted bone morphology, trabecular patterns of the proximal and middle phalanges, and distinctive radiopaque and radiolucent features as the anatomical features that aided the identification process. The hand can be an important skeletal element for radiographic positive identification because it contains 27 individual bones for comparative analysis.

KEYWORDS: forensic science, forensic anthropology, human identification, hand radiographs, validation study, *Daubert*

Positive identification of unknown human remains is a critical part of the medico-legal investigation. Common methods of obtaining a positive identification include fingerprints, DNA analysis, comparative dental radiography, and comparative medical radiography. Despite their common utilization, there is a lack of scientific literature that has validated the results of these identification techniques. In particular, very little research has validated the comparative medical radiography of post-cranial skeletal morphology. This should be a concern to the forensic science community, specifically forensic anthropologists, pathologists, and radiologists.

A recent Supreme Court ruling from 1993, *Daubert v. Merrell-Dow Pharmaceuticals, Inc.* (1) requires that the standard for scientific evidence in a federal court is "that the reasoning or methodology underlying the testimony must be scientifically valid" (2:1035). The *Daubert* test of scientific evidence relies on a preliminary ruling by the judge on whether the scientific theory or technique is scientifically valid based on testing, rates of error, peer review through publication, and "widespread acceptance". Validation studies, therefore, are important for each discipline in the American Academy of Forensic Sciences because scientists need to be able to demonstrate that their scientific testimony is supported by the *Daubert* test. *Daubert* is a federal court requirement for evidence, but many states have accepted it for their evidence standards. Some states have rejected *Daubert*, preferring to uphold the *Frye v. United States* standard of evidence that was adopted by federal courts and most individual states in the years since 1923. *Frye* states that scientific testimony must have general acceptance in its field, but does not refer to scientific validity (2,3). Further information on a state-by-state basis can be found in Bohan and Heels (2).

Despite the urging and awareness by forensic anthropologists to *Daubert* and its implication for forensic anthropologists (3,4), there are very few published studies that assess the validity of different methods for obtaining a radiological identification of human remains (5–12). The majority of publications concerning radiological identification from human skeletal remains are case studies that focus either on the cranium (13–15), or on postcranial skeletal remains (15–22). Additionally, comparative medical radiographic research has been conducted on a number of post-cranial bones (6–9,15,23–25). Finally, the role of radiology in mass disasters (26–29), and even in a case of the intentional fragmentation of skeletal remains (30) has also been reported.

Greulich (31,32) first discussed the importance and reliability of hand-wrist radiographs for human identification. When faced with the task of identifying American war dead, he realized there was a need for methods other than just dental radiography to identify human skeletal remains. Greulich's analysis of approximately 500 radiographs and vast experience with age determination from hand-wrist radiographs helped him determine that skeletal features formed in late childhood remain unique throughout life. Utilizing features, such as overall bone shape and trabecular patterns of the proximal and middle phalanges, he concluded that, "it is quite possible to establish the identity of an individual from the skeletal features visible in a roentgenogram of the hand and wrist" (32:764). Greulich's analysis of 40 pairs of hand radiographs of same-sex, identical twins led him to determine that there were resemblances between each identical pair of twins, but "there were, in every instance, some features which made it possible to distinguish the hand

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and wrist bones of one person from those of his or her own twin" (32:763).

A more recent case report has specifically addressed trabecular bone microstructure of the hand and its utilization for positive identification (33). Kahana et al. (11) used the technique of radiographic absorptiometry and a computerized image analyzer to examine a sample of 305 hand radiographs from 103 postmenopausal females. Based on the high correlation of radiographs from the same individuals and the low correlation of radiographs from different individuals, they concluded that trabecular pattern comparison is a reliable method to positively identify unknown skeletal remains. Research on other skeletal elements has also determined that comparing trabecular patterns and their relationship with radiopaque and radiolucent features is a valid technique for positive identification (6,8,9).

The purpose of this current study is to test the ability of forensic scientists to correctly match postmortem hand radiographs to a sample of antemortem hand radiographs. This study demonstrates that the comparative medical radiography of the human hand is a valid method for positive identification. In addition, this paper discusses the anatomical criteria which prove to be the most useful and least beneficial to the examiners in the identification process. Finally, this validation study is designed to comply with the *Daubert* guidelines for scientific evidence.

Materials and Methods

In order to investigate the validity of posterior-anterior radiographs of the hand for human identification purposes, a series of radiographs was taken on human cadavers since it is not feasible to generate a large sample of hand radiographs of living individuals from which a postmortem subsample could be radiographed again. For this project, 40 radiographs from 40 anatomical cadavers from the Michigan State University Gross Anatomy Lab represent the radiographs of antemortem hands. A subsample of hands was subsequently removed from 10 of the cadavers and skeletonized to simulate the postmortem sample. Therefore, the term "antemortem" radiographs used in this paper actually refers to the 40 radiographs of fleshed cadaver hands, while "postmortem" radiographs refers to the 10 radiographs of the skeletonized subsample. All radiographs were taken with a General Electric Amx2 portable X-ray unit. The cadavers are all part of the Willed Body Program directed by the Michigan State University, Department of Radiology, Division of Anatomy.

In order to investigate the validity of posterior-anterior radiographs of the hand for human identification purposes, a series of radiographs was taken on human cadavers. The "antemortem" radiographs were taken in a manner to replicate the standards employed by radiographic technicians for posterior-anterior hand radiographs of living patients in clinical situations (23,34). Thus, the distance between the X-ray source and the film cassette was maintained at 40 in., while the central ray was directed perpendicular to the film at the third metacarpophalangeal joint. The settings on the X-ray machine were set at 50 kVp, while mAs varied between 8–10 mAs for the antemortem radiographs. A plexi-glass device was used to force the hands of the cadavers to remain flat on the radiographic film, as a living patient would position their hand in a clinical situation (Fig. 1). This "hand press" measured 34.3 cm wide by 36.8 cm long, and was constructed of two separate pieces of 1.3 cm thick polycarbonate plexi-glass. When a hand was positioned in the hand press, there was plexi-glass superior to and inferior to the cadaver hand. Plastic knobs attached to screws at the four corners of the hand press were then tightened to flatten the cadaver hand on the film.

FIG. 1—*The "Hand Press". This is the device that was used to position the cadaver hands for the posterior-anterior hand X-rays.*

TABLE 1—*Age and sex distribution of antemortem and postmortem radiographs.*

Radiograph Sample	n=	Age		Sex	
		Range (years)	Mean (years)	Male	Female
Antemortem Radiograph	28	(46–102)	81.1	17	11
Unknown Antemortem Radiograph	12	N/A	N/A	N/A	N/A
Postmortem Radiograph	9	(67–102)	86.0	3	6
Unknown Postmortem Radiograph	1	N/A	N/A	1	
Total Radiographs	50				

The mean age, age range, and sex of the individuals whose hands were used for both the antemortem and postmortem specimens are provided in Table 1. Age and sex are not available for all of the antemortem specimens, because some of the hands radiographed in this group were isolated hand/wrist specimens. It is a fair assumption that the majority of the isolated hands are elderly, similar to the rest of the sample. The age of one postmortem hand was also unknown because it was an isolated specimen.

The "postmortem" sample was generated by removing 10 of the left hands, proximal to the wrist joint, from the above 40 individuals. These hands were then processed at the Michigan State University Forensic Anthropology Lab into bony specimens by removing all the soft tissue, following standard osteological preparation technique (35). The specimens were rearticulated using a low temperature hot glue gun. Care was taken to articulate the bones in an orientation that was similar to the antemortem radiograph. The lead author took several trial postmortem radiographs and compared each to the appropriate antemortem radiograph in an effort to maximize the number of bones of the hand that were in the correct orientation. A final radiograph of each reconstructed hand displaying the best orientation was then selected, in essence mimicking a skeletal postmortem radiograph. These postmortem radiographs were taken duplicating the same clinical standards that were used for the antemortem films. The above process is similar to the methods employed by forensic anthropologists when they attempt to conduct a radiological identification. To the authors' knowledge, no previous researchers have conducted a study in which a radiograph from a fleshed body part is compared to a postmortem radiograph from the body part after the remains were skeletonized and rearticulated. The radiographic settings for the skeletal postmortem radiographs were 50 kVp and 3 mAs. The mAs setting for the postmortem radiographs was slightly lower than required for the antemortem radiographs, because there was not plexi-glass on top of the bones, as there was for the antemortem radiograph sample. It should be noted that the comparison of radiographs of the same bone with different radiographic settings does not prevent a positive identification from trabecular pattern (33).

The validation component of this study examined the accuracy of volunteer participant examiners making correct matches between antemortem and postmortem radiographs of the hand. Twelve participant examiners, six Ph.D. forensic anthropologists, five forensic anthropology graduate students, and one forensic pathologist, received 50 radiographs from 40 different individuals. They compared 40 "antemortem" radiographs of fleshed hands from known individuals (identified by numbers 1–40), to 10 "postmortem" radiographs of bony hands from an unknown portion of the antemortem sample (identified by the letters A–J). The participants were instructed that no more than one individual represented each one of the 10 postmortem radiographs from the group of the original 40, thus there was the possibility that the postmortem radiographs did not have a match. The participants worked independently, without assistance from others, to match the correct postmortem radiograph to its appropriate antemortem match, or to identify which postmortem film did not have an antemortem match. They did not have any information concerning the age, sex, or ancestry of the individuals represented by the radiographs. The 50 radiographs were all presented as radiographs of left hands, even though 8 of the hands from the antemortem pool were right hands. In no case were the radiographs of a right and left hand of the same specimen used. Films of right hands were reversed to simulate left hands in order to maintain the sample size and to prevent examiners from making matches based on excluding right or left hands during the process. The participants were also asked to note on a data sheet which specific anatomical and morphological features were used for identification purposes, and completed a short survey after their test. The use of human subjects as volunteer participant examiners in this research was approved and in accordance with the rules created by the University Committee on Research Involving Human Subjects at Michigan State University.

Results

The group accuracy rate for the twelve participant examiners was 95% (Table 2). Profession, experience level, and specific training in radiological identification affected the ability to perform well in the study. The accuracy of each different group of examiners can be found in Table 2. All six Ph.D. forensic anthropologists with experience in radiological identification, and four experienced forensic anthropology graduate students had a perfect score in matching the 10 postmortem hand radiographs, which included one radiograph that did not have a corresponding antemortem match. (See Fig. 2 for an example of a correct match between an antemortem and postmortem hand radiograph.)

TABLE 2—*Accuracy of examiners for matching radiographs.*

Observer ID#	TP* (max = 9)	TN† (max = 1)	Correct Matches (TP + TN) (max = 10)	FP‡	FN§	Incorrect Matches (FP + FN)	Sensitivity‖ (TP/TP + FN)	Specificity†† (TN/FP + TN)	Accuracy (TP + TN/TP + TN + FN + FP)
F. Anthro (PhD)									
1	9	1	10	0	0	0	1.00	1.00	1.00
2	9	1	10	0	0	0	1.00	1.00	1.00
3	9	1	10	0	0	0	1.00	1.00	1.00
4	9	1	10	0	0	0	1.00	1.00	1.00
5	9	1	10	0	0	0	1.00	1.00	1.00
6	9	1	10	0	0	0	1.00	1.00	1.00
Group Total	*54*	*6*	*60*	*0*	*0*	*0*	*1.00*	*1.00*	*1.00*
F. Anthro Grad Student									
7	9	1	10	0	0	0	1.00	1.00	1.00
8	9	1	10	0	0	0	1.00	1.00	1.00
9	9	1	10	0	0	0	1.00	1.00	1.00
10	9	1	10	0	0	0	1.00	1.00	1.00
11††	6	0	6	1	3	4	0.67	0.00	0.60
Group Total	*42*	*4*	*46*	*1*	*3*	*4*	*0.93*	*0.80*	*0.92*
F. Pathologist									
12	7	1	8	0	2	2	0.78	1.00	0.80
SUM – All Groups	**103**	**11**	**114**	**1**	**5**	**6**	**0.95**	**0.92**	**0.95**

* True positive.
† True negative.
‡ False positive.
§ False negative.
‖ True positive rate.
†† True negative rate.
‡‡ First-year graduate student.

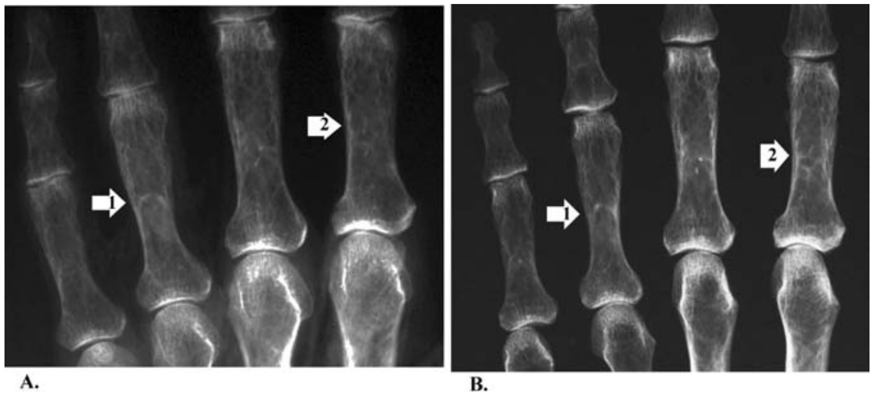

FIG. 2—*An example of a correct match between antemortem and postmortem, posterior-anterior hand radiographs. Figure 2A is the antemortem radiograph and Fig. 2B is the postmortem hand radiograph. The numbered arrows (1&2) refer to corresponding features between the two radiographs. In both cases, details of matching trabecular patterns are indicated.*

Two other statistical methods have been employed to assess the examiner's results in this type of validation study (36). Both sensitivity and specificity were calculated along with accuracy (Table 2). These are important results in validation studies, because sensitivity determines the true positive (TP) rate. This is the rate at which the examiner correctly matched antemortem and postmortem radiographs. Specificity is the true negative (TN) rate, or the rate at which the observer correctly did not find a match for a postmortem radiograph in the antemortem pool of radiographs. A false negative (FN) occurred when the examiner incorrectly rejected a match between a postmortem and antemortem radiograph. In other words, the examiner failed to recognize the existing match, because they stated there was no match. On the other hand, a false positive (FP) occurred when the observer incorrectly matched a postmortem to an antemortem, when in fact the postmortem did not have a match in the antemortem pool or was matched incorrectly. Overall, in this study, there was only 1 false positive result, and a total of 5 false negative results. The sensitivity of the 12 examiners was 95%, while their specificity was 92%. The observers in this study shared none of the same incorrect identifications.

An additional component of this study was to identify the skeletal features and elements of the hand that were utilized by the examiners to make identifications. This section of the datasheet was open-ended, in that examiners were not provided with a list of features or categories to use for identification purposes. Each feature used for identification of the 10 postmortem radiographs was tabulated (Table 3). The result was seven different categories that examiners listed as morphological criteria for identification. Shape/morphology of the bones; trabecular pattern; morphology of distinctive radiopaque and radiolucent features; and degenerative changes, such as osteophytic lipping and osteoarthritis, were the four categories with the largest number of references. Only results for correct identifications were analyzed, thus the postmortem radiograph without an antemortem match did not have any identification markers. Participant examiners identified the phalanges of the hand, some specifically noted the proximal phalanges, and the metacarpals as the skeletal elements most useful for identification purposes. Distal phalanges and carpals were most frequently noted as the skeletal features that were least helpful in the identification process.

Discussion

Previous publications have addressed the concept of elapsed time between antemortem and postmortem radiographs and its effect on skeletal features such as bony contours and trabecular patterns used for human identification. In this study there is no elapsed time between films, because the simulated antemortem radiographs in this study are of deceased individuals from the Michigan State University Anatomy Lab. Therefore, there has not been any subsequent bone growth or remodeling in the time between the exposure of the "antemortem" and "postmortem" radiographs.

Nonetheless, Sauer et al. (16) conclude that time spans between radiograph films from 10–23 years still allow for a comparison of morphological features associated with the vertebral column. In another report, Sauer and Brantley (37) also specifically addressed the development of degenerative changes in the distal phalanges and interphalangeal joints of an individual's hand between antemortem and postmortem radiographs over a span of 10 years. They concluded that although degenerative changes had occurred, there was

TABLE 3—*Skeletal features used by examiners to identify postmortem radiographs.*

PM Film ID#	Shape/Morphology of Bones	Trabecular Pattern	Morphology of Radiopaque and Radiolucent Features	Degenerative Changes (lipping/arthritis)	Medullary Cavity Morphology	Size	Healed Fracture
A	6	7*	3	1	1	1	
B	6*	5	5	3	1		
C	8*	2	3	3			
D	7*	3	4	4	1		
E	7*	6	4	2	1		
F	8*	5	4		1	3	
G	8*	3	5	1	1		
H	3	5	4	6*	2		
J	5	4	4	7*			1
SUM	58	40	36	27	8	4	1

* Denotes the feature that was cited the most number of times for identification of each radiograph.

still enough morphological consistency to make a positive identification. The morphological consistency of the trabecular pattern of shoulder, hip, and knee radiographs of a second individual was also stable over a period of 10 years (37). One study examining foot radiographs with a time span between presurgical and postsurgical radiographs of two months to four years revealed that trabecular patterns of the foot bones correlated highly with identification (8). In a case report, a radiological positive identification, later confirmed by DNA analysis, was made based on two bones, the first metacarpal and distal phalanx, of the hand which had a two year period between the antemortem and postmortem radiograph (33). Perhaps, the most compelling research regarding the stability of hand trabecular patterns has been conducted by Kahana et al. The importance of this research should not be understated, because despite a sample population of elderly women with a proposed high rate of bone mineral loss over time, trabecular patterns remained stable enough over two to six years to be markers of individuality (11).

One previous study on experience level and its effect on radiological identification has shown, as expected, that those with the most medical and anatomy experience performed better than a group with less experience (38). This study, however, involved radiologists only. In a recent validation study of chest radiographs, a forensic anthropologist had the highest overall accuracy when compared to two radiologists and a forensic pathologist (7). Furthermore, the authors of the chest study note that the forensic anthropologist relied on a morphological approach for comparison, while the others used a diagnostic approach, emphasizing the comparison of pathologies. Another validation study on the role of the hyoid for identification did not reveal any differences in success between forensic pathologists, forensic anthropologists, and forensic anthropology graduate students, as they all had perfect scores (6).

This study of hand radiographs confirms the role of experience and training in radiographic human identification. The forensic anthropology graduate student with 60% accuracy noted on the survey that the examiner's experience with radiological identification was limited. The sensitivity of all the examiners was 95%, while overall specificity was 92%. If the inexperienced graduate student and the forensic pathologist categories of examiners were eliminated, then both the sensitivity and specificity of the remaining 10 experienced examiners was 100%. This confirms the idea that training and experience has an affect on one's ability to correctly match antemortem and postmortem radiographs.

The groups of skeletal features that were most frequently identified as the most useful for identification were consistent with other studies dealing with radiological identification. Participants in the hand study used bone shape/morphology, trabecular patterns, radiopaque and radiolucent features, and degenerative changes the most frequently for identification purposes. Examiners identified many of the same types of individualizing markers that Greulich (31,32) and others (6,8,9,17) noted in previous radiological identification research.

One possible limitation regarding the results of this study by the authors was that identification of the elderly population in this study would be solely based on degenerative changes of the hand bones, because no time elapsed between radiographs. Degenerative changes were the most frequent trait for the identification of only two postmortem radiographs, whereas shape/morphology of bones was the highest reference for six of the films (Table 2). Thus, it appears that degenerative changes were not the primary basis for identification in this study. The second limitation was that sexual dimorphism would also make identification too simple. In fact, there was one postmortem radiograph that three examiners noted for its large male size and utility for identification (PM film F), while the "petite size" of another radiograph (PM film A) was cited for identification once. The largest hand of the postmortem sample was never incorrectly matched by any of the examiners, but the petite one was matched incorrectly on one occasion. Certainly, these results do not imply that the participant examiners did not use size to group or sort radiographs, but other correct matches did not contain any mention of overall bone size.

Even when examiners noted that some of the bones were not oriented properly or offered insufficient visibility in the radiographs, they were still able to make accurate matches. The distal phalanx was one of the skeletal elements noted for its poor exposure quality in the films. This is not unexpected when one realizes that the center ray of the x-ray machine is aimed at the third metacarpophalangeal joint in clinical situations. Thus, it is imperative that forensic scientists replicate, and have knowledge of, the same standards for the exposure of postmortem radiographs (6). The carpal bones were also cited as problematic for the examiners, probably due to orientation issues. The rearticulation of the carpals was difficult because the bones articulate in a complex manner and there is a great deal of soft tissue that binds the bones together in life. Despite these problems, the carpals were cited for identification purposes multiple times. Importantly, this study avoids the type of orientation problems previous researchers believe hindered the results of their overall accuracies (7).

Conclusion

This validation study asked twelve participant examiners to attempt to match 10 simulated postmortem radiographs of skeletonized hands to a pool of 40 simulated antemortem radiographs of fleshed cadaver hands. The research demonstrates that the comparative analysis of hand radiographs is a valid method for positive identification. The hand is a reliable anatomical structure for radiographic identification because it contains 27 bones that are available for comparison. By following the procedures outlined in this study, or others stressing correct orientation between antemortem and postmortem films, posterior-anterior hand radiographs can be an important technique for the identification of skeletal remains. The overall accuracy of the twelve participant examiners was 95%, but the six Ph.D. forensic anthropologists and four forensic anthropology graduate students experienced with radiological identification had an accuracy of 100%. This method appears to satisfy the requirements of *Daubert's* guidelines of scientific validity by establishing a standard methodology for hand radiograph analysis, testing the technique, and noting rates of error. The study also illustrates that examiners with less experience and radiological training may be less qualified to perform comparative radiographic analyses. Participant examiners noted bone morphology; trabecular patterns of the proximal and middle phalanges; the morphology of distinctive radiopaque and radiolucent features; and degenerative changes as the anatomical features that aided the identification process.

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