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PAPER

ANTHROPOLOGY

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Skeletal Identification by Radiographic Comparison: Blind Tests of a Morphoscopic Method Using Antemortem Chest Radiographs*,†,‡

ABSTRACT: This study investigated the value of antemortem (AM) and postmortem (PM) radiographs of the claviculae and C3-T4 vertebrae to identify skeletons of missing U.S. soldiers from past military operations. In total, 12 field-recovered skeletons and AM chest radiographs of 1460 individuals were used. For each skeleton, examiners analyzed an array of AM chest radiographs (up to 1000 individuals) and attempted to identify the correct PM/AM radiographic match. When examiners were able to compare all images within a single test, only true-positive identifications were made. When AM radiographs were presented one-at-a-time, in sequential order, and without examiners having knowledge of array size, erroneous identifications resulted but they were almost exclusively made by untrained examiners (accuracy = 35% vs. 90% for trained examiners). This study demonstrates the value of chest radiographs for the identification of disarticulated and even eroded skeletons, but only when methods are wielded by trained examiners.

KEYWORDS: forensic science, X-rays, skeletal identification, forensic anthropology, clavicle, vertebrae

Chest radiographs hold potentially high value for skeletal identification because they provide an antemortem (AM) record against which postmortem (PM) images can be compared and because this type of radiograph is the most common of any infracranial body region (1,2). Moreover, chest radiographs form a component of an individual's medical record; consequently they are typically easier to locate than dental radiographs (3,4). In addition, chest radiographs sometimes form the only avenue for identification when other identification methods (such as dental records or mitochondrial DNA) cannot be used.

Despite several published case reports that use comparisons of AM/PM chest radiographs to help identify disarticulated skeletons (5–11), no large-scale controlled scientific studies have been pursued to systematically quantify method accuracies. Such studies are warranted so that methods with known errors can be applied in forensic casework (12,13). While four validation studies using chest radiographs and soft tissue–encased remains have been published (1,14–16), the results of these studies cannot be directly applied to skeletons because joint congruencies are lost in the defleshed state (1,16), and skeletonized remains are subject to PM alteration (e.g., erosion). Nevertheless, results of validation studies on soft tissue remains hold some general applicability, so they are outlined below.

In 1974, a validation was sought for an identification in a Massachusetts forensic case. A single examiner (a radiologist) received 110 chest radiographs (timing of radiographic capture, i.e., PM or AM, is not reported in the original study) and attempted to match them to radiographs of 100 individuals, thus 10 individuals served as nonmatches (14). All pairings were reported to be correct (14).

In 1977, Martel et al. (15) conducted a study where two assessors (a senior radiologist and a senior radiology resident) collaborated to evaluate nine AM chest radiographs from eight unknown individuals against an array of 25 different AM radiographs. The two observers were in agreement in their identifications in eight of nine cases and worked to resolve their single difference before arriving at their final identification decisions, which across all trials were 100% correct (15).

In 1994, Hogge et al. (16) conducted a study of different body regions, but included "frontal" chest radiographs from two individuals. These radiographs were presented to 53 examiners who possessed different levels of radiographic training and experience and who attempted to identify the authentic match from four AM radiographs in each case (one target and three nontargets). For the chest radiographs, correct identifications were reported 94% of the time (16).

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In 2002, Kuehn et al. (1) examined chest radiographs from a total of 42 individuals (30 individuals each with matching AM and PM radiographs, and 12 individuals with only AM radiographs), across three test designs using four examiners (a forensic anthropologist, pathologist, and two radiologists). In the first test, Kuehn et al. (1) used three sets of eight AM radiographs and five PM radiographs. Examiners were required to identify one of the eight AM radiographs as a unique match to each of the five PM radiographs. The second round of tests included six radiographic arrays comprised of five AM and one PM radiograph. Examiners were asked to match the one PM radiograph to one of the five AM radiographs, but not all PM radiographs were supplied with an authentic match. The third type of test included 10 sets of AM and PM radiograph pairs, where examiners decided whether a match existed for each pair. As a reliability check, all tests were repeated using the same examiners but with renumbering and reshuffling of the radiographs so that the they were composed of different combinations, and in some cases, different ratios of matching (target) and nonmatching (nontarget) images. Overall, Kuehn et al. (1) reported a mean correct response rate across all 62 tests of 80% (92% for the forensic anthropologist alone).

Because the accuracies reported for soft tissue intact remains are relatively high, they offer hope to similar methods applied to disarticulated skeletons. However, several attributes of the above-mentioned studies favor positive outcomes and so should be acknowledged. One limitation is the small identification universes were employed (sometimes as tiny as four to five individuals for any single test). For the Massachusetts study, which holds a sizable sample (N = 110), the assessment protocol provides a major limitation. That is, this study undertook multiple pair-matching tasks from the same single array; so, as the study progressed the radiologist could have double checked his/her identification decisions via leftover nonmatching pairs. In addition, identification decisions would have been facilitated via the decreasing array size each time a pair match was made. Many of the above-mentioned studies also did not use real PM radiographs (they used duplicate AM images), so their results are not applicable to real-life forensic casework where PM radiographs are generated. Also in studies where real PM radiographs were used, the PM radiographs were often not independently produced by each examiner, and thus major sources for inter-observer error were eliminated from these investigations.

The simultaneous presentation of all AM array radiographs to an examiner also increases the ease of the tests because identifications can potentially be made on a poor degree of morphological correspondence, so long as other individuals in the AM array provide for even worse matches (17–20). Therefore, while these studies provide strong suggestive evidence that AM/PM comparisons of chest radiographs hold value for identification, the accuracies generated probably represent ceiling estimates because they were generated in a relative, rather than absolute manner. That is, these studies asked "to which one of these individuals do the remains provide a match," rather than "do these remains match this individual."

The aim of this study was to assess the value of AM and PM radiographs for the identification of disarticulated skeletons, but in such a way as to avoid the above-mentioned limitations inherent in past studies on soft tissue–encased remains. Furthermore, we aimed to use test material that would produce data applicable to contexts of fallen U.S. soldiers from past military operations, and in particular to the 855 individuals recovered from the Korean War who are buried as unknowns in the National Memorial Cemetery of the Pacific (NMCP) in Hawaii. These NMCP individuals are of special interest to the Joint POW/MIA Accounting Command (JPAC) because mtDNA and dental records cannot be used to identify them. That is, AM dental radiographs were not routinely captured or archived until the Vietnam War; written dental records that exist are often hampered by transcription inaccuracies; and mtDNA is problematic to extract from the remains because of cross-linking induced by mortuary treatments that were used just prior to the repatriation of the remains (21). On the other hand, chest radiographs exist for approximately 70% of those missing from the Korean War as a result of tuberculosis screening that was universally adopted across the U.S. Armed Forces in 1942 (22,23).

Materials and Methods

Overview

AM radiographs of 1460 individuals and PM radiographs from 12 male skeletons were used in this study (Tables 1 and 2). All materials were drawn from cases pertaining to fallen U.S. military personnel from World War II and the Korean War. Study materials and assessment protocols were specifically selected to generate a range of tests with varying degrees of difficulty (see below).

In each test, a single skeleton was presented to examiners along with an array of AM radiographs. Examiners were

TABLE 1—*Skeletons used in this study.*

Skeleton	War Era	Preservation	Elements Presented to Examiners	Claviculae Sampled for mtDNA	Age (Years) At First Radiograph	Age (Years) At Last Radiograph	Age (Years) At Death	Time Interval Between Last Radiograph and Death (Years)
1	**KW**	**Good**	**Claviculae, C3-T3**	**No**	**20.8**	**25.7**	**26.2**	**0.5**
2	**WWII**	**Good**	**Claviculae, C3-T3**	**No**	**19.0**	**19.0**	**~20.3**	**~1.3**
3	**KW**	**Fair**	**Claviculae, C5-T5**	**No**	**18.9**	**18.9**	**20.5**	**1.6**
4	**KW**	**Fair**	**Claviculae, C3-T4**	**No**	**19.9**	**19.9**	**22.3**	**2.4**
5	**KW**	**Fair**	**Claviculae, C1-C7**	**Yes**	**17.3**	**17.3**	**18.5**	**1.2**
6	KW	Fair	Claviculae, C1-C7	Yes	NA	NA	16.0–21.0*	NA
7	KW	Fair	Claviculae, C1-C7	Yes	NA	NA	23.0–32.0*	NA
8	**KW**	**Fair**	**Claviculae, C2-C7**	**Yes**	**20.7**	**25.2**	**26.6**	**1.4**
9	**KW**	**Fair**	**Claviculae, C3-T2**	**No**	**18.8**	**21.8**	**22.2**	**0.4**
10	KW	Fair	Claviculae, C3-T3	No	NA	NA	17.0–22.0*	NA
11	**KW**	**Poor**	**Claviculae only**	**No**	**18.6**	**18.6**	**19.2**	**0.6**
12	**WWII**	**Poor**	**Claviculae only**	**No**	**18.3**	**18.3**	**19.3**	**1.0**

Bold type marks the skeletal remains with accompanying AM radiographs.
KW, Korean War; WWII, World War II; NA, Not applicable.
*Age estimated from the skeletal remains using well-established anthropological methods.

TABLE 2—*Results of the identification trials conducted in this study.*

Array Type	Simultaneous				Sequential								Summary Statistics					
Test No.	1	2	3	4	5	6	7	8	9	10	11*	12*						
Array Size (n)	10	50	100	1000	25	40	25	30	40	55	45 [10]	40 [17]						
Sequence No. of Target	10	29	98	679†	22	NA	NA	13	23	NA	44 [9]	20 [12]	No. of Correct Matches (TP + TN)	No. of Incorrect Matches (FP + FN)	No. of Tests Attempted	Sensitivity (TP/TP + FN)	Specificity (TN/TN + FP)	Accuracy (TP + TN/ No. of Tests Attempted)
Examiners																		
Trained																		
1	TP	TP	TP	TP	TP	TN	TN	TP	FN	TN	FP [TP]	CCE [TP]	10	2	12	0.89	0.75	0.83
2	–	–	–	TP	TP	TN	TN	TP	–	–	–	–	5	0	5	1.00	1.00	1.00
Total													15	2	17	0.91	0.83	0.88
Untrained																		
3	–	–	–	–	TP	TN	TN	FN	–	–	–	–	3	1	4	0.50	1.00	0.75
4	–	–	–	–	FP‡	TN‡	FP‡	FP‡	–	–	–	–	1	3	4	0.00	0.25	0.25
5	–	–	–	–	FN	TN‡	FP‡	TP‡	–	–	–	–	2	2	4	0.50	0.50	0.50
6	–	–	–	–	FN	–	–	TP‡	–	–	–	–	1	1	2	0.50	NA	0.50
7	–	–	–	–	FP	FP	FP	FP	–	–	–	–	0	4	4	0.00	0.00	0.00
8	–	TP	–	–	–	–	–	–	FP	FP	FP [FP]‡	FN	1	4	5	0.50	NA	0.20
Total													8	15	23	0.50	0.27	0.35

TP, true-positive response (correct identification); FP, false-positive response (incorrect identification); TN, true-negative response (correct no-match); FN, false-negative response (incorrect no-match); CCE, correctly could not exclude.

*These trials used very incomplete remains and modified sequential and simultaneous trials.

†For examiner 2, the sequence of this array was reshuffled making the position of the target person 433 in the sequence of 1000.

‡Indicates trials where the examiner did not take his/her own PM radiographs, but used those produced by examiner 1.

[ ] Indicates results for simultaneous trials that were conducted following sequential tests (see Results for further details).

instructed to produce PM radiographs with the skeletal remains in a position representative of the standard used for postero anterior (PA) chest radiography. This gave rise to 12 identification tests where examiners tried to determine whether any matches existed between the PM and AM radiographs. No test reused AM radiographs, and not more than one authentic AM/PM match was used in any identification trial. Nine tests included a correct match, while three tests presented a skeleton that had no authentically corresponding AM image (Table 2). AM radiographs in each array were presented to examiners all-at-once (=a total of four simultaneous arrays) or one-at-a-time (=eight sequential arrays).

AM Radiographs

All of the AM radiographs used in this study were stereoscopic photofluorograms that were captured at military medical screening stations between 1940 and 1953 and stored on microfilm (typical dimensions of a single image = 112 × 91 mm). Having exceeded their estimated life expectancy of 40 years (23), and perhaps not having been stored under strict archival conditions for acetate film and/or washed properly at the time of processing, many of these radiographs were deteriorated. Primarily, this included film channeling and crazing (24); however, most individuals were represented by more than one film and usually one of these was in good/fair condition (Figs 2–9). If an individual had multiple AM radiographs, all radiographs were presented to examiners during the tests irrespective of their condition.

Skeletons

The 12 field-recovered skeletons used in these tests varied in preservation state (Table 1). The simultaneous tests used some of the most intact bones, while the sequential trials used less intact bones. Except in the first and second tests, all claviculae and vertebrae had some degree of surface exfoliation and erosion as typical for casework concerning field-recovered remains. In some cases the spinous processes of vertebrae, whole centra, transverse processes, and the lateral/medial extents of the claviculae were missing (see Figs 4–9). Tests 5–8 of the sequential trials had a clavicle missing >50% of its mid-shaft because of prior mtDNA sampling, and tests 11 and 12 used highly eroded and/or incomplete claviculae without any vertebrae (see Figs 8 and 9). Fewer vertebrae were made available to examiners in the sequential trials to push the capabilities of the methods. This was also the reason for the inclusion of tests 11 and 12, where no vertebrae were used and the claviculae were highly eroded.

Examiners

Eight examiners undertook various combinations of the 12 trials (Table 3). Six examiners were anthropologists and two were odontologists. Few examiners were able to complete all 12 trials (see Table 3 for details) because of case pressures impinging upon the availability of the skeletal remains and other commitments of the examiners' time.

Examiner 1 was the main researcher involved in the project and possessed the most familiarity with radiographic anatomy and the quality of the Korean War radiographs. Examiner 2 was specifically trained by examiner 1 using radiographs of 90 individuals and test 1 and test 3 as practice. This included coaching on thoracic anatomy, chest radiograph interpretation, and radiographic comparison methods. Because the other examiners (i.e., 3–8) received no in-depth pretest mentoring, they were categorized as being "untrained." This categorization should not be interpreted to mean that these examiners had no understanding of the radiographic

TABLE 3—*Details for examiners who took part in this study.*

			Prior Experience				
Examiner	Discipline	Qualification	Radiographic Interpretation	Chest Radiograph Interpretation	Anatomy	Other Relevant Details	Practice Using Test 1
1	FA	Ph.D.	Yes	Yes	Whole body	Previously employed as lecturer in gross anatomy, dissection experience, familiar with WWII/Korean War era radiographs	No
2	FA	M.A.	Yes	Yes	Skeleton and dermatoglyphics	Osteology classes, currently training as a fingerprint expert	Yes
3	FA	M.Sc.	Yes	Yes	Whole body	Osteology classes, gross anatomy classes	Yes
4	FO	D.D.S.	Yes	No	Principally craniofacial	4 years forensic experience with dental radiographic comparisons, undertook whole body dissection during dental training, trained in clinical radiography	No
5	FO	D.M.D.	Yes	No	Craniofacial only	4 years forensic experience with dental radiographic comparisons, trained in clinical radiography	Yes
6	FA	Ph.D. (ABFA)	No	No	Whole body	Previously employed as autopsy technician, gross anatomy teaching assistant	Yes
7	FA	M.A.	No	No	Skeleton	Osteology classes, exposed to WWII/Korean War era radiographs when constructing arrays for tests 1–4, 9–12	Yes
8	FA	Ph.D. (ABFA)	No	No	Whole body	Previously employed as gross anatomy teaching assistant, dissection experience, exposed to WWII/Korean War era radio graphs when constructing arrays for tests 5–8	No

FA, Forensic Anthropologist; FO, Forensic Odontologist; ABFA, Diplomate of the American Board of Forensic Anthropology.

comparison principles (examiners were all drawn from disciplines where radiographic comparison is routine); no clinical radiography training; no experience or training undertaking radiographic comparisons; or no familiarity/training with the osseous structures of the chest—as some did (see Table 3 for details). Untrained examiners received only limited information on radiographic comparison methods, a demonstration on how the skeletal remains should be positioned on the image receptor prior to image capture, a one-page condensed method description; and most received test 1 as an unmentored practice run (see Table 3).

PM Radiographs

Examiners took their own PM radiographs wherever possible and used these images for the identification tests. This was mandatory for examiners 1 and 2 and encouraged for untrained examiners. Where it proved impractical or futile (i.e., bones were not correctly sided or orientated in the PA position) or where the skeletal remains were no longer available for use, the PM radiographs taken by examiner 1 were used in their place (see Table 3 for details). A HOLOGIC® RADEX™ digital X-ray system (Bedford, MA) was used for expediency and ease of repeated PM image capture (Fig. 1).

Examiners were restricted to only the claviculae, lower cervical vertebrae and upper thoracic vertebrae for PM radiography (see Table 2). These bones formed the subject of the investigation because they display a relatively large degree of variation; are easily seen on chest radiographs; and represent some of the best preserved parts of the chest in skeletons recovered from prior battle fields. Furthermore, this step helped standardize the study because practitioners were not free to decide which bones of the thorax would be utilized.

Examiners were directed to radiograph the skeletal elements in positions representative of those occupied at the time of AM radiography. This could be achieved because AM radiographs represented standardized PA projections where the backs of hands were placed on the hips and below the costophrenic angles, chin on top of the image receptor, shoulders rotated toward the image receptor, and a source-image distance of *c.* 72 inches used ([25,26]; see, e.g., Fig. 1). Thus, it could be estimated that the body was likely placed: facing directly ahead, anterior side of the thorax in contact with the image receptor, neck in extension, shoulders rotated forward (almost aligning the long axis of the clavicle parallel to the image receptor), and slight, if any, posterior rotation of the clavicle (= slight arm abduction; see, e.g., Fig. 1).

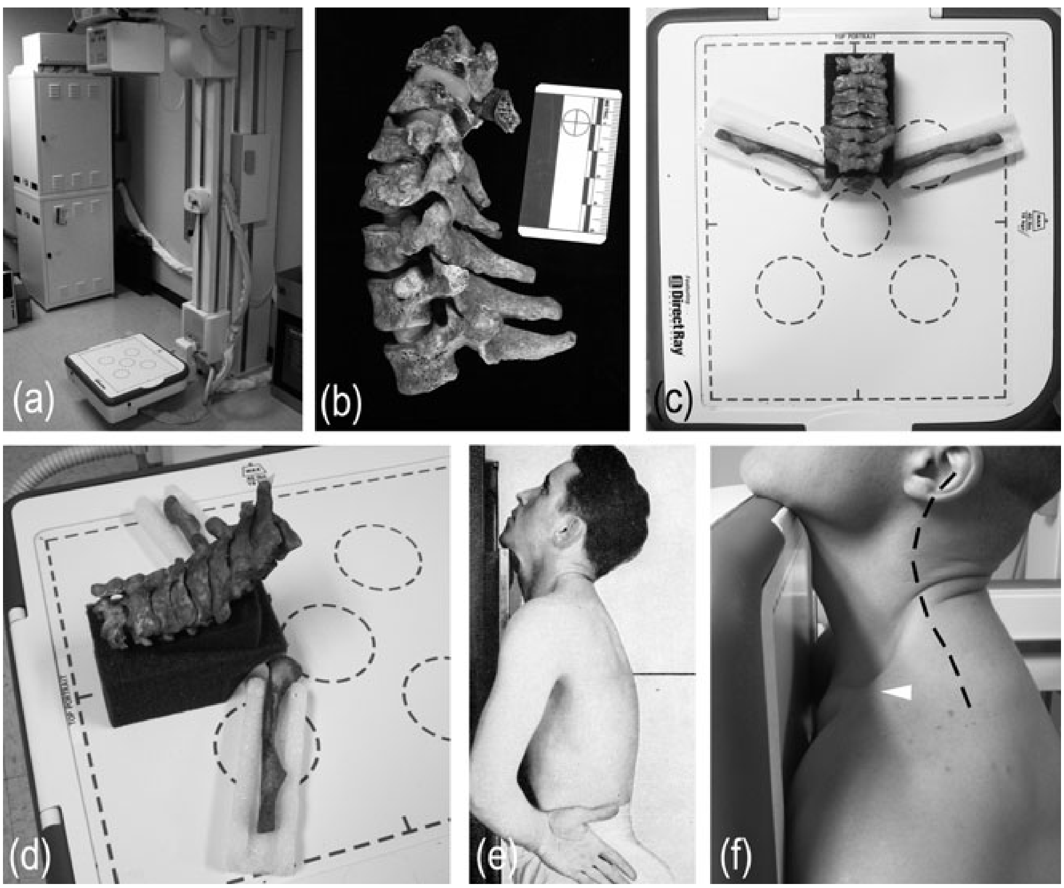

FIG. 1—*PM radiography of the skeletal remains. (a) The X-ray machine set so that the image receptor is horizontal to hold the skeletal remains. (b) Lateral view of the vertebrae used in test 4. Spacing/support between the vertebrae has been provided using Utility Wax (Heraeus Kulzer®, South Bend, IN). (c) The skeletal remains from test 2 positioned on the image receptor prior to radiography—foam stands have been used for bone stabilization. (d) An oblique view of the test 2 remains. Note that the medial ends of the clavicle extend past the foam supports so that the lateral ends are slightly further from the image receptor than the sternal ends. (e) Position of a living subject for PA chest X-ray projection according to military guidelines. Image reproduced from Military Roentgenology (26, p. 322). (f) A lateral superior view of a 24-year-old Marine positioned for PA chest radiography. Image illustrates the clavicle position (white arrow) not seen in (e). The dashed line represents the approximate location of the vertebral bodies.*

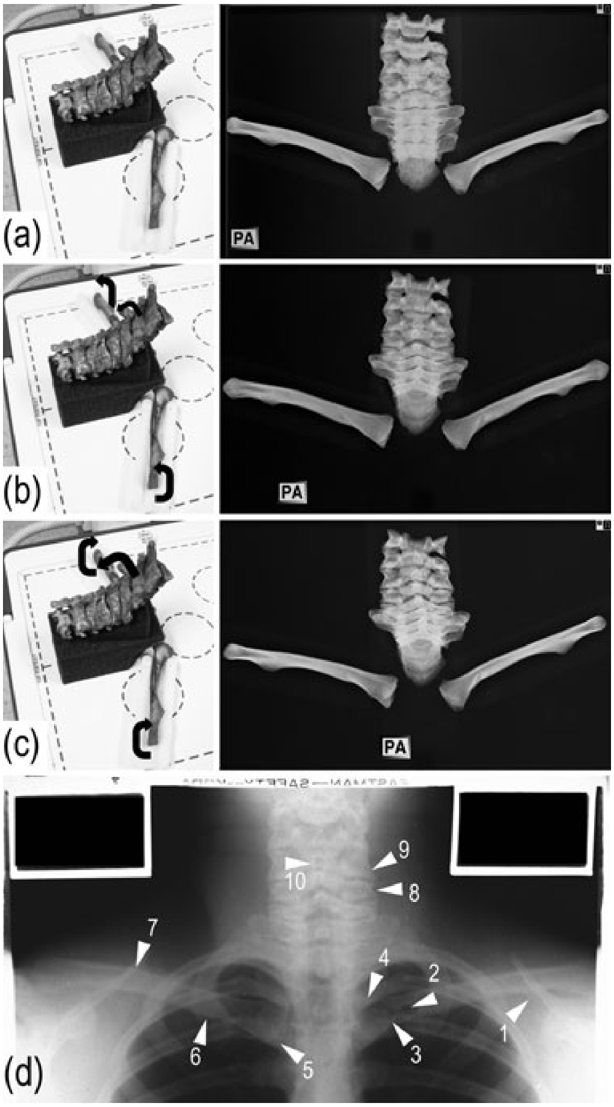

FIG. 2—*Setting the remains (from test 2) to obtain three PM radiographs. (a) Examiner 1's best blind estimate of the living position. Resulting PM radiograph is shown at the right. (b) Setting of the remains to obtain the first PM "buffer" image. The claviculae are (slightly) rotated so the conoid tubercles become more superiorly placed and less obvious on the radiograph. The inferior vertebrae are also elevated to incline the column anteriorly. The resulting PM image is shown to the right. (c) Setting of the remains to obtain the second PM "buffer" image. The claviculae are rotated away from the best estimated position and in a direction opposite to (b). The vertebral column is also inclined even further anteriorly. (d) The matching AM radiograph for these remains. Ten consistencies used by both examiners 1 and 8 to form their identification decision in test 2 have been highlighted. Because of poor contrast on the original image, the picture has been exposure enhanced for publication purposes (Adobe® Photoshop® CS3, San Jose, CA; "Exposure" setting: exposure = +0.39, offset = 0.3257, gamma correction = 0.26). Note that these consistencies (and many more) were visible on the unadjusted radiograph. 1 = prominent conoid tubercle below shaft of left clavicle; 2 = similar shaped and proportioned rhomboid fossa translucency on left clavicle; 3 = similar obliquely shaped medial rhomboid fossa edge with high density on left clavicle; 4 = tight curve on superior medial margin of left clavicle (on PM radiographs it can be seen to rise toward a spine); 5 = change in radiodensity at medioinferior edge of right clavicle; 6 = subtle bulge of inferior right clavicular border; 7 = flexion point of right superolateral margin of the clavicle; 8 = left laterally narrowed C6 lateral mass with tight convexity of lateral edge and sharp lips at superior and inferior extents; 9 = long straight oblique lateral margin of left inferior articular process of C5; 10 = large clearly bifid spinous process of C5.*

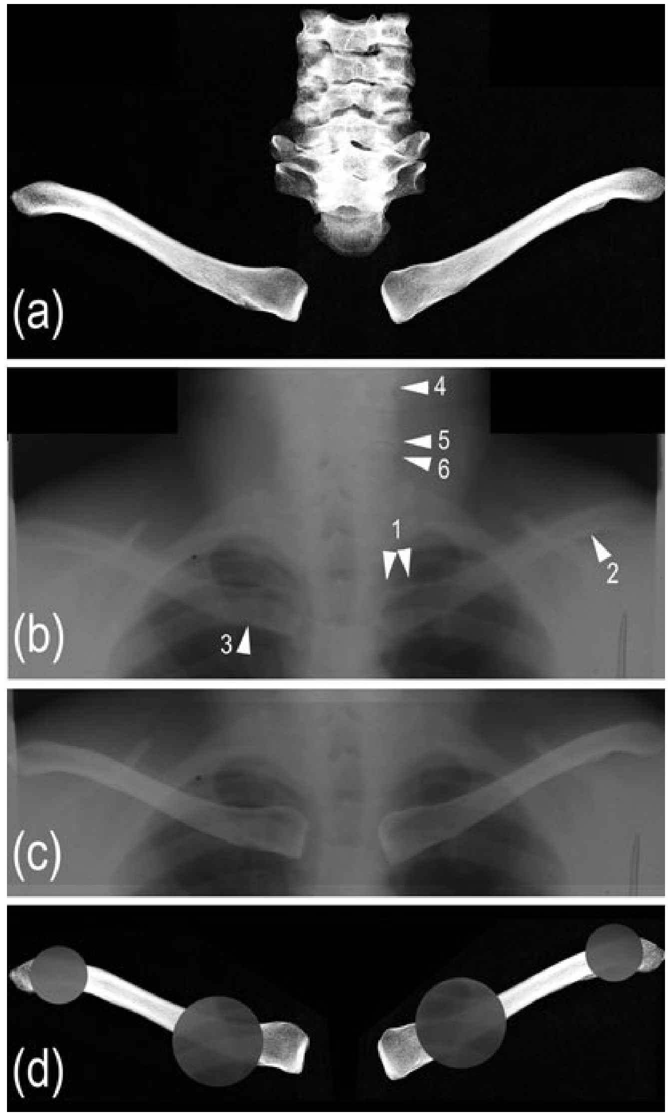

FIG. 3—*Matching PM and AM radiographs from test 1 (n = 10 simultaneous test). (a) PM radiograph produced by examiner 1. (b) AM radiograph. Although numerous points of anatomical correspondence exist between (a) and (b), six consistencies have been highlighted: 1 = two tubercles on superior medial margin of left clavicle; 2 = conoid tubercle projection below the left clavicular shaft; 3 = interrupted cortical bone margin at rhomboid fossa of right clavicle; 4 = tightly flexed indentation on the left lateral aspect of C4; 5 = oblique an inferior angulation of left C5-6 facet joint, with curved articular surfaces and a lateral bulge of the C5 left inferior articular process; 6 = wedge-shaped left lateral neural arch (bounded by the C6 left apophyseal joint facets). (c) Superimposition of the claviculae from the PM radiograph over AM radiograph (note near exact correspondence). (d) Mask of PM claviculae over AM radiograph but with windows in the PM image to view the AM image.*

The medial ends of the claviculae were set at the level of the T3–T4 lamina after data by Lakshmanan et al. (27), who found that the superior margins of the medial claviculae fall between the levels of T2 and T3 in 62% of individuals radiated antero posteriorly. Thus, the level of the claviculae would be slightly lower in the PA position because of their greater distance from the image receiver and position above the center ray. As in the living posture (see, e.g., Fig. 1), the vertebrae were positioned farther from the image receptor (*c.* 60 mm) than the claviculae, which in turn, were very close (*c.* 10 mm; see, e.g., Fig. 1). Data

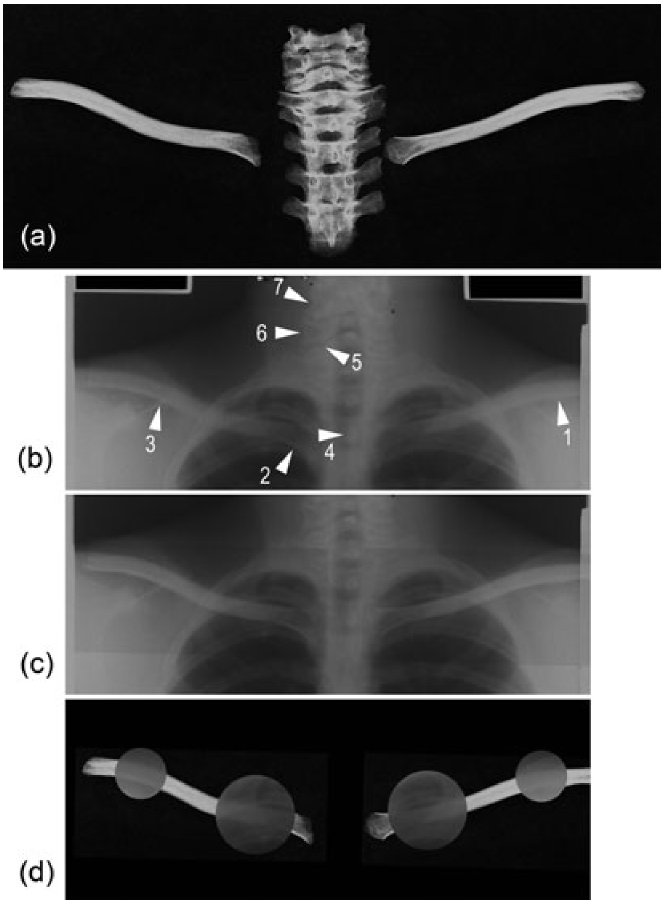

FIG. 4—*Matching PM and AM radiographs from test 3 (n = 100 simultaneous test). (a) PM radiograph produced by examiner 1. (b) AM radiograph. Although numerous anatomical correspondences exist between (a) and (b), seven consistencies have been highlighted: 1 = slight projection of elongated conoid tubercle below the left clavicular shaft; 2 = radiopaque inferior medial border of right clavicle; 3 = double shadow of inferior midshaft border of right clavicle; 4 = vertically elongated and slender spinous processes of T3 (with a flat right lateral margin); 5 = acute angle in radiopaque bone structure visible in region of right lamina on C7 near right superior articular facet; 6 = tall flaring wedge-shaped outline of right lateral extent of C6; 7 = tightly flexed indentation on the right lateral aspect of C5; (c) superimposition of claviculae from the PM radiograph over the AM radiograph (note near exact correspondence). (d) Mask of the PM claviculae with windows to view, without obstruction, the AM radiograph.*

by Gilad and Nissan (28) were used to approximate the intervertebral space (*c.* 5 mm); and a < 2 mm separation was used between the zygapophyseal joints to simulate the articular cartilage.

For each test, examiners captured three PM images of the skeletal remains (Fig. 2). The first image represented each examiner's best blind estimate of the AM position, while the two subsequent images represented "buffer views" in anticipation of PM prediction error and approximations of the standard position created at the time of AM radiography. For the best estimate, the rhomboid fossae of the claviculae were faced postero inferiorly and so that the base of the conoid tubercle was hidden behind the shaft from the anterior perspective. In regard to the vertebrae, C3-T2 were positioned superior to the sternal end of the claviculae and with the spinous processes vertically oriented so that they gave clear circular-like perimeter outlines on the radiograph (see Fig. 2). Although uncertainty existed for all of the above-mentioned procedures, it never prevented close approximation of the AM radiographs (see Figs 2–9).

Although not specifically measured, the claviculae were rotated about their long axis *c.* <5° for the buffer views and the articulated vertebrae were rotated up to *c.* 50° about an axis perpendicular to the median plane (see Fig. 2). PM radiographs were captured using a fixed image receptor size (*c.* 350 × 430 mm) and X-ray parameters of 50 kVp, 100 mA, and 0.04 sec exposure. At image capture, examiners were freely permitted to adjust the inverse topography to produce the best user-defined visualization and examiners were directed to mirror reverse each PM radiographic image as is standard for PA projection of the chest in living subjects (26,29).

Image Comparisons

Examiners compared their PM images with the AM radiographs to make identifications on the basis of correspondence in osseous structures, as widely commented on in the literature (see [5–8,15,30–35] or for reviews [8,30,31]). As made clear to all examiners, this included overall bone shape, patterns of cortical density and thickness, trabecular morphology, and fossae presence/shape/density. This, however, represented the extent of instruction that untrained examiners received on image comparison.

Examiner 2 was additionally coached by examiner 1 to use a gestalt approach, where the entire morphology of the osteological structures captured in the PM image, and as visible on the AM image, were to be used in the formulation of identification decisions. This required each individual's radiographs to be carefully analyzed and interpreted, rather than a predetermined and limited set of features being checked off during comparison. Of course, examiner 2 was familiarized with typical traits/regions that held value (bony spurs/tubercles at the sternocleidomastoid insertion; rhomboid fossae presence/absence and form; degree and direction of arching of the claviculae; form of conoid process; form of spinous process outlines; form of T1 transverse processes; slope of the zygapophyseal joints; C7 neural arch outline, and outline shape of vertebral column edges), but it was emphasized that this should not represent the extent of the search and that unusual or defining characteristics in other bony regions should not be disregarded in favor of the aforementioned traits.

Examiner responses for each trial were classified as positive (match present) or negative (match absent), and in each case could be true (correct) or false (incorrect), giving rise to four possible results: true positive, false positive, true negative, and false negative. Method performance was assessed using accuracy, sensitivity, and specificity measures relative to these performance terms (for detailed discussion, see [36]). Accuracy represents the overall correct identification rate from the total number of trials; sensitivity measures the rate at which examiners correctly found a match for PM radiographs; and specificity measures the rate at which examiners correctly did not find a match for the PM radiographs (for formulae, see Table 3).

Simultaneous Arrays

Simultaneous arrays presented all AM radiographs to the examiner at once, and the size of these arrays increased successively to ensure increasing difficulty (*n* = 10, 50, 100, and 1000). Because examiners were required to identify one individual from the array, it was implicit that a single authentic match existed in each case. No time limits were set for comparisons, although times for each trial were tracked (a single pass through the *n* = 1000 simultaneous trial [test 4] took trained examiners between 30 and 60 h of

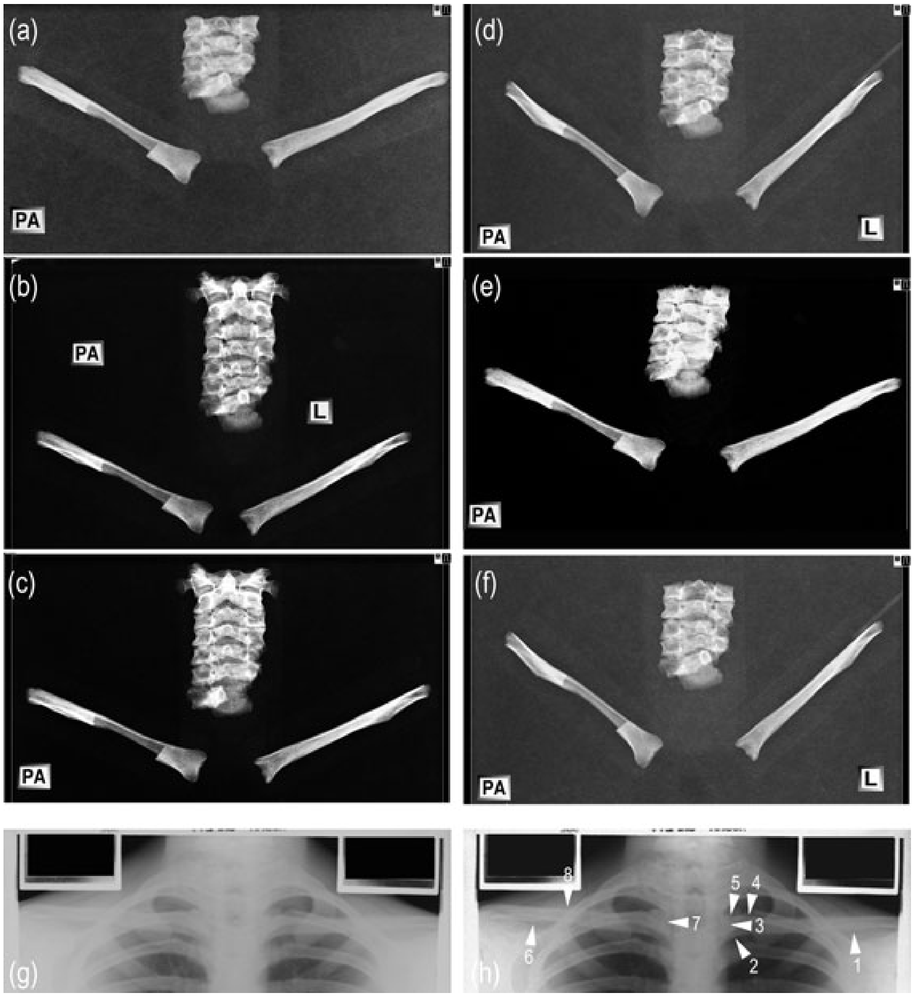

FIG. 5—*Matching PM and AM radiographs from test 5. (a–c) "Best estimate" PM radiographs produced by examiners who obtained a true-positive identification: (a) examiner 1, (b) examiner 2, (c) examiner 3. (d–f) "Best estimate" PM radiographs produced by examiners who made erroneous identification decisions: (d) examiner 5 (false negative), (e) examiner 6 (false negative), (f) examiner 7 (false positive). (g) AM radiograph of the target individual. (h) Exposure enhanced target image, used for publication purposes only (Adobe® Photoshop® CS3; "Exposure" setting: exposure = −0.18, offset = +0.4098, gamma correction = 0.19). Eight consistencies commonly used by examiners 1–3 to obtain true-positive responses have been highlighted: 1 = conoid prominence below inferior margin of left clavicle; 2 = tight downward curvature of inferomedial margin of left clavicle; 3 = strong indentation of sternal articulation of left clavicle; 4 = out-bulging on superomedial aspect left clavicle 5 = tight upward curvature of superomedial margin of left clavicle; 6 = conoid prominence below inferior margin of right clavicle; 7 = slight indentation of sternal articulating surface of the right clavicle; and 8 = out-bulging slightly lateral to the mid-shaft region on the superior margin of the right clavicle.*

nonstop radiographic comparison). Examiners were permitted to undertake computer-assisted superimpositions of the AM and PM images to finalize their decisions in any trial. This was performed by referencing the three-dimensional morphological appearance of the skeletal remains against the radiograph and making fine manual adjustments.

For the simultaneous trials, all AM radiographs were selected so that the quality and preservation state of the nontarget radiographs matched those of the target, but were otherwise randomly selected from the same sample of radiographs representing missing military personnel held at the Joint POW/MIA Accounting Command. For the $n = 1000$ array, radiographs of 999 nonmatching individuals were preselected from a larger sample of 6102 people by an independent observer on the basis that the excluded radiographs possessed the greatest differences in claviculae size, shape, and/or morphology of the rhomboid fossa to the correct match. This step filtered out individuals who represented obvious nonmatches, thus increasing the rigor of the identification task (20).

Sequential Arrays

Eight sequential trials presented AM radiographs, one-at-a-time, to an examiner who after viewing the radiographs for one individual was forced to make a decision of "match" or "no match" before termination of the test (in the case of the former response) or seeing the next image in sequence (in the case of the latter answer). The examiner could not review prior radiographs or decisions, and additionally the radiographs were handed to the examiner from behind a barricade so that the test administrator and the AM radiographs could not be viewed or anticipated. This precluded examiners from knowing the size of each test's identification universe. In addition, examiners were notified that correctly matching AM radiographs would not necessarily be encountered in any of the tests, even if arrays were completely exhausted. Five of the sequential arrays included radiographs from individuals that provided an authentic match to the remains and three trials did not (tests 6, 7, and 10; Table 3).

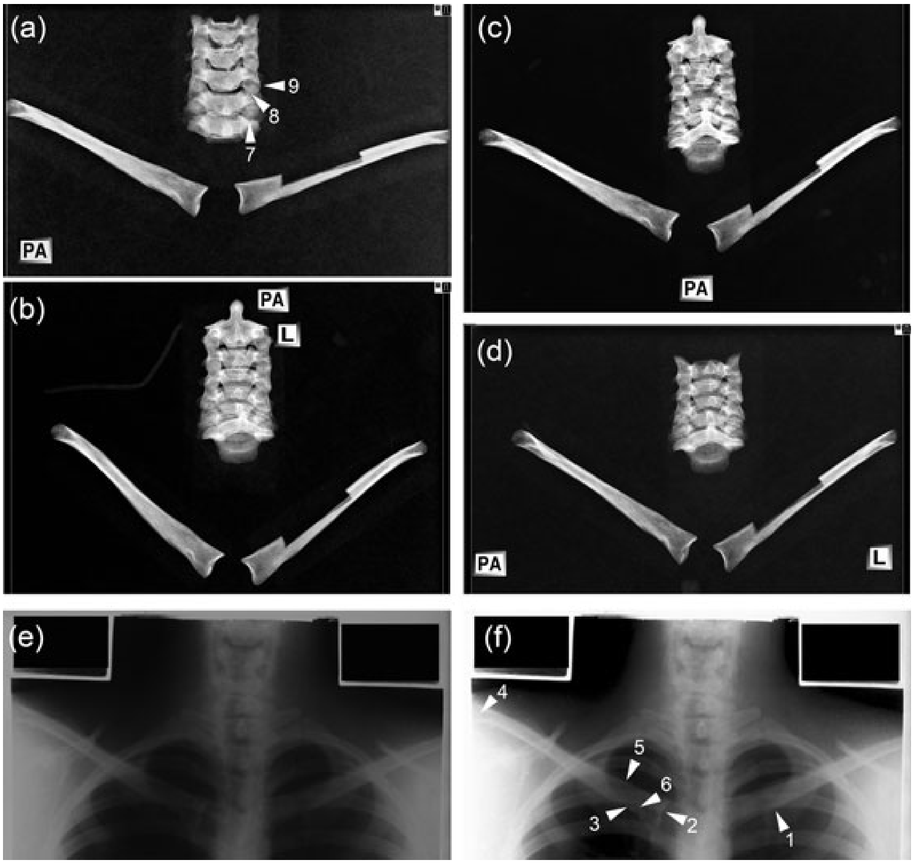

FIG. 6—*Matching PM and AM radiographs from test 6. (a,b) "Best estimate" PM radiographs produced by examiners who obtained true-positive identifications: (a) examiner 1, (b) examiner 2. (c,d) "Best estimate" PM radiographs produced by examiners who made erroneous identification decisions: (c) examiner 3 (false negative), (d) examiner 7 (false positive). (e) AM radiograph of the target individual. (f) Exposure-enhanced target image, used for publication purposes only (Adobe® Photoshop® CS3; "Exposure" setting: exposure = +1.39, offset = −0.0059, gamma correction = 1.31). Five consistencies used by examiners 1 and 2 to obtain true-positive responses have been highlighted, and three additional vertebral characteristics used by examiner 1 have been numbered: 1 = out-bulging of the inferior margin of the left clavicle; 2 = marked indentation of the superior part of the sternal articulation of the right clavicle; 3 = presence of long rhomboid fossa on right clavicle; 4 = large medullary translucency within the acromial end of right clavicle; 5 = out-bulging of superior margin of right clavicle toward the median plane; 6 = short but marked opacity of the medial edge of the rhomboid fossa; 7 = radiopaque line running through the left lateral mass of C7; 8 = radiotranslucent left superior articular process of C6; 9 = silhouette of the left inferior articular process/facet of C5.*

Because the skeletal remains for test 10 exhibited marked rhomboid fossa, only radiographs of nontarget individuals with large marked rhomboid fossae were chosen for this array. So as to avoid potentially huge time investments on the sequential trials (because no image could be revisited), image superimpositions were not permitted.

To ensure reasonable examiner throughput and to avoid examiner procrastination, a time pressure for identification was established in the sequential trials (3 min), which when breached resulted in the examiner being notified of subsequent time-intervals every few minutes to gently encourage decisions. We avoided a strict time limit as other authors have used (see, e.g., Hogge et al. [16] who used a 5 min cut off) so that examiners could exceed arbitrary times as they found necessary, more closely approximating casework where vastly more time might be needed for more difficult cases. Tests were also run back-to-back wherever possible not only to facilitate examiner throughput, but also to ensure that examiners were not sheltered from fatigue effects. This was important because in some contexts (e.g., mass disasters, mass graves, and during JPAC casework) multiple searches of sizable identification universes (>50 individuals) can be required under short time frames.

Results

Overview

Only true-positive identifications were made in the simultaneous tests (accuracy = 100%, sensitivity = 100%, $n = 6$ trials). Erroneous identification responses were only observed during the sequential trials, and errors were almost exclusively made by untrained examiners (Table 2). Across the 30 sequential identification trials that did not include the very incomplete remains (tests 5–10), there were a total of seven true-positive, 10 false-positive, seven true-negative, and four false-negative results: accuracy = 53%, $n = 30$ trials; sensitivity = 64%, $n = 11$ trials; specificity = 47%, $n = 19$ trials (Table 2). Examples of PM radiographic images used by examiners for comparisons are presented across Figs 2–9. Note that the single clearest AM radiograph available for each target individual has been reproduced here.

Trained Examiners

Trained examiners made no errors across the simultaneous tests: accuracy = 100%, $n = 5$ trials; sensitivity = 100%, $n = 5$ trials.

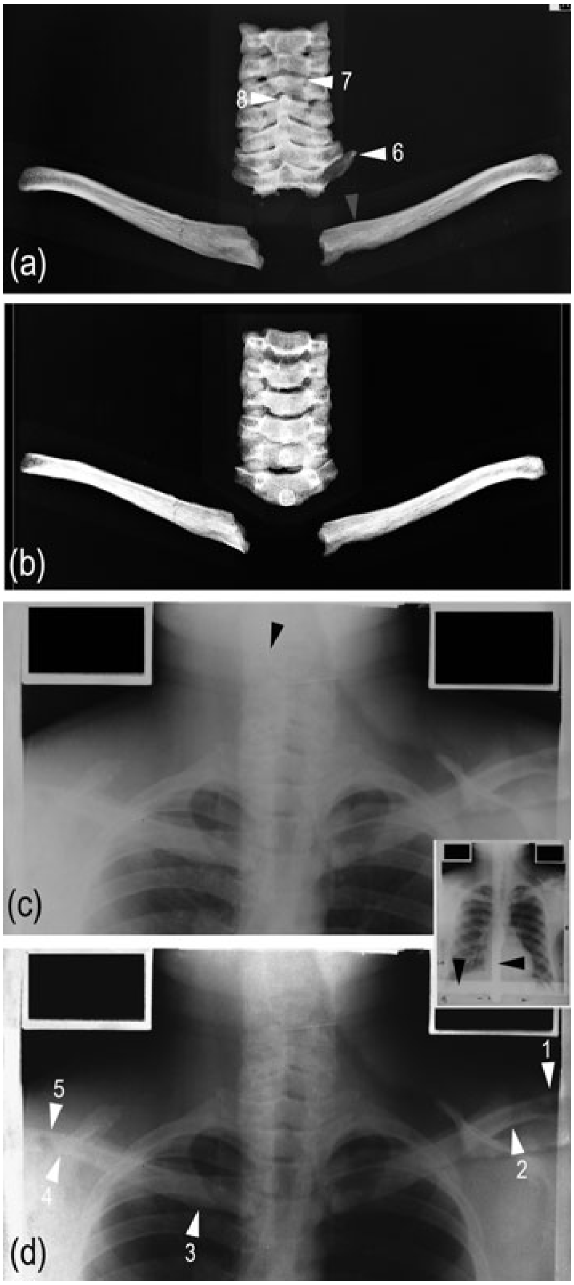

FIG. 7—*Matching PM and AM radiographs from test 9. (a) PM radiograph produced by examiner 1 (1st buffer image). Gray arrow indicates an out-bulging on the mediosuperior margin of the left clavicle which is not visible on the AM image. (b) Collage of PM radiographs taken by examiner 8 (vertebrae = best estimate; claviculae = 1st buffer image). The collage is used here only to decrease space requirements. Original radiographs were used during the study. (c) AM radiograph. Note the faded region down the anatomical right margin of the vertebral column, which forms part of a larger T-shaped pattern most clearly seen across the whole radiograph (see black arrows on image inset). (d) Exposure-enhanced AM radiograph, used for publication purposes only (Adobe® Photoshop® CS3; "Exposure" setting: exposure = +0.60, offset = 0.1275, gamma correction = 0.34). Despite erroneous identifications by both examiners 1 and 8, five consistencies are apparent between the PM and AM images: 1 = bulbous lateral end of left clavicle; 2 = radiopaque lateral inferior cortical margin of left clavicle and with sharp inward bending; 3 = pronounced outward bending of inferomedial border of right clavicle; 4 = radiopaque lateral inferior cortical margin of right clavicle and with sharp inward bending; and 5 = flat lateral region of lateral superior margin of the right clavicle. Three further consistencies are visible on examiner 1's PM radiograph: 6 = tapered and superiorly orientated left transverse process of T2; 7 = transparent neural arch of C5 revealing outline of the C4's body; 8 = small rounded spinous process of C6.*

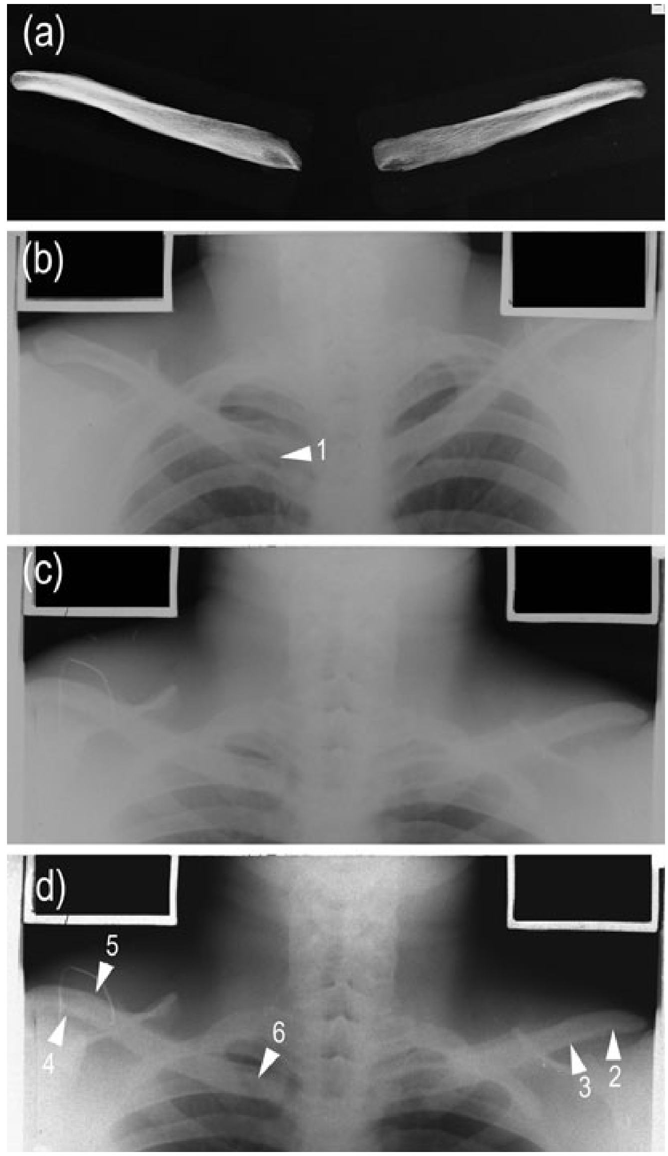

FIG. 8—*Matching PM and AM radiographs from test 11. (a) PM radiograph produced by examiner 1 (best estimate image), and as used by examiner 8. Note the surface erosion and the missing medial and lateral ends. (b) Radiograph representing the false-positive match made by both examiner 1 and examiner 8. Note the similarity in clavicle shapes and the right rhomboid fossa (white arrow = 1). (c) Authentically matching AM radiograph. (d) Exposure-enhanced AM radiographic image, used for publication purposes only (Adobe® Photoshop® CS3; "Exposure" setting: exposure = +0.08, offset = +0.4569, gamma correction = 0.16). Five consistencies used by examiner 1 to obtain a true-positive identification on the simultaneous trial have been highlighted: 2 = tight in-bending of inferolateral aspect of left clavicle; 3 = radiopaque cortical margin of inferior lateral aspect of shaft of left clavicle; 4 = slight visibility of conoid tubercle on right clavicle below inferior clavicular margin; 5 = subtle out-bending on superolateral margin of right clavicle, 6 = small obliquely orientated rhomboid fossa on right clavicle.*

Across the more difficult sequential trials, but excluding the highly eroded remains, trained examiners made only one error (a false negative): accuracy = 90%, $n = 10$ trials; sensitivity = 80%, $n = 5$ trials; specificity = 100%, $n = 5$ trials. Across all trials, including the highly eroded skeletal remains, trained examiners made two errors (a false negative and a false positive): accuracy = 88%, $n = 17$ trials; sensitivity = 91%, $n = 11$ trials; specificity = 83%,

$n = 6$ trials. The mean decision time for trained examiners in the sequential trials was 34 sec (range = 2–664 sec, $n = 295$ decisions).

Untrained Examiners

Despite taking twice as long as trained examiners to make their decisions (68 sec, range = 3–591 sec, $n = 364$), untrained examiners performed poorly on the sequential trials. One untrained examiner did not achieve a single correct result across any of the four trials he/she participated in (examiner 7, Table 2), and this examiner possessed a tendency to identify individuals very early in the tests (two-of-four false-positive identifications were made within the first five individuals of the array sequences). While no sequential trial appeared to draw excessively large numbers of erroneous responses, test 6 almost exclusively drew true-negative responses. On debriefing, examiners often commented that the skeleton used in this trial possessed an elevated superior clavicle margin, which significantly assisted the formulation of identification decisions.

Untrained examiners made 13 errors across sequential trials that did not include the highly eroded remains and most erroneous responses were false positives: accuracy = 35%, $n = 20$ trials; sensitivity = 50%, $n = 6$ trials; specificity = 29%, $n = 14$ trials. Across all trials, including one simultaneous test ($n = 50$) and the highly eroded skeletal remains, untrained examiners made 15 errors (4 false negative and 11 false positive): accuracy = 35%, $n = 23$ trials; sensitivity = 50%, $n = 8$ trials; specificity = 27%, $n = 15$ trials. These results severely reduced the overall performance of the methods recorded in this study (see Overview).

Extreme Tests (Tests 11 and 12)

Because trained examiners performed well on tests 1–4 (simultaneous arrays) and tests 5–10 (sequential arrays), very incomplete and eroded claviculae were used in tests 11 and 12 to push the methods and the examiners further (see Figs 8*a* and 9*a*). In test 11, sequential protocols were employed, and both examiners (1 and 8) made a false-positive identification of the same nontarget individual (no. 11) in reference to the same skeleton (see Fig. 8). To obtain additional data on method accuracy, the trial was re-run using some of the remaining unseen nontarget individuals from the sequential trial, but using simultaneous test conditions (array size = 10). Under this context, examiner 1 (trained) correctly identified individual nine as the target (true-positive response), while examiner 8 (untrained) incorrectly identified individual seven (false-positive response).

From the outset of test 12, both examiners made it clear that the skeletal remains were too incomplete to yield purposeful identification decisions under the sequential format that was planned. This trial was, therefore, modified from an identification context to an exclusion/inclusion context by using the responses: "exclude" and "cannot exclude." To provide further information on method accuracy, a simultaneous test ensued if the target individual was correctly labeled as "cannot exclude," and it included all the individuals that received a "cannot exclude" response during the sequential trial. Examiner 1 excluded 23 of 40 individuals from the test leaving 17 individuals as possible matches, one of whom was the target. In the subsequent simultaneous array using these 17 persons, three individuals were retained as possible matches (correctly including the target person). Although reluctant to pick any single individual, examiner 1 correctly chose individual 12 as the match when forced to select one (Fig. 9). Examiner 8 excluded 25 of 40 individuals in the sequential trial, including the target individual, and so never progressed to a simultaneous assessment.

Discussion

In the hands of trained examiners, we found the claviculae and C3-T4 vertebrae sufficient to generate an accuracy ≥ 88%, sensitivity ≥ 91%, and specificity ≥ 83%, despite the fact that disarticulated bones had to be orientated in estimated AM bone positions under blind conditions. This success rate is impressive, especially in the context that this study possessed a number of measures that increased the test stringency (see Materials and Methods). Thus, this investigation probably yielded conservative estimates of the method's accuracy, so the lower accuracies reported should not be taken to indicate a lesser value of the methods in contrast to other radiographic comparison studies (1,14–16). Given that high accuracy rates were observed in this study using realistic and nonideal contexts, it will be interesting in future studies to see the results when ideal specimens and radiographs are used.

Clearly, the results of this study highlight the sufficiency for identification decisions to be based on chest radiographs displaying normal skeletal morphologies, even when AM image quality or skeletal preservation is suboptimal. This counters claims that radiographic comparison methods hold questionable value with regard to skeletons (1,16) and/or that "chest film tends to be less useful [than radiographs of other body regions]" (32, p. 754). In our opinion, the use of disarticulated skeletal elements holds some clear advantages over soft tissue-encased remains because bone positions can be precisely manipulated to obtain meticulous image superimpositions that provide stronger support toward a match.

The finding that the method works successfully on radiographs of nonideal image clarity awards the method broad forensic relevance because even higher accuracy rates can be expected when radiographic images possess higher clarity. Moreover, current tests on low-clarity radiographs validate the method for use in JPAC cases where images of similar poor clarities are encountered. Because normal skeletal morphologies were also found to provide a sufficient basis for identification, it makes sense that this information should be factored into cases where trauma, medical intervention, anatomical anomalies, and pathological morphologies are observed (9,37–40), so that all of the information evident from an AM radiograph is used to provide for the most comprehensive and robust identification decision. This approach has not previously been emphasized in the literature, where anatomical anomalies or medical interventions have been reported (and/or proposed) for the primary basis of identification decisions (9,37–40).

Findings that the method largely failed in the hands of untrained examiners (accuracy = 35%, sensitivity = 50%, specificity = 27%) is consistent with patterns observed by Hogge et al. (16) and supports their conclusions that (i) level of expertise influences success and (ii) untrained examiners should be cautiously employed in forensic casework. In the present study, however, the gap observed between trained and untrained examiners was large (55% as opposed to 10% reported by Hogge et al. [16]), particularly because all our examiners were professional forensic experts from disciplines where AM/PM comparisons are routine. In comparison, the 10% difference observed by Hogge et al. (16) occurred between radiology residents (4 years medical training plus months to years of diagnostic radiology training) and high school students, and even the latter lay group obtained a very high performance score (mean of 74% correct responses).

We suspect that a difference in the test protocols employed by Hogge et al. (16), in comparison with our study, is the principal reason for the above-mentioned difference. For example, Hogge et al.'s (16) study used the following: simulated PM radiographs

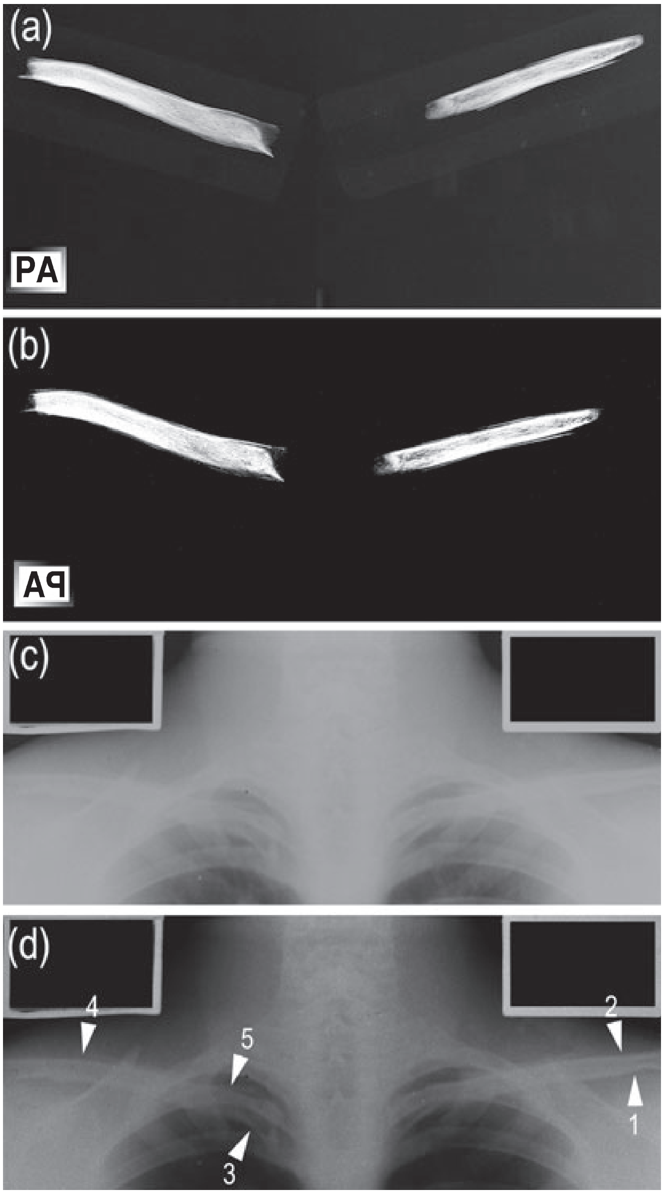

FIG. 9—*Matching PM and AM radiographs from test 12. (a) PM radiograph produced by examiner 1 (best estimate image). Note the extensive erosion, especially to the medial and lateral ends. (b) PM radiograph produced by examiner 8. (c) Matching AM radiograph. (d) Exposure-enhanced AM radiographic image, used for publication purposes only (Adobe® Photoshop® CS3; ''Exposure'' setting: exposure = +0.24, offset = +0.3157, gamma correction = 0.15). Four consistencies used by examiner 1 to obtain a true-positive identification have been highlighted: 1 = superiorly directed in-bending of the inferior margin of the lateral aspect of the left clavicle; 2 = inferiorly directed in-bending of the superior margin of the lateral aspect of the left lateral clavicle; 3 = thin oblique but radiopaque line representing the cortical bone on the inferomedial aspect of the right clavicle; 4 = point of flexion on lateral superior margin of right clavicle; 5 = small out-bending on superomedial aspect right clavicle (also visible on exfoliated margin of the PM radiograph).*

(i.e., a second AM image); a predetermined and identical PM radiograph across all examiners for each test; only simultaneous AM arrays; arrays of only four radiographs; arrays that always presented targets individuals; and AM images that were produced on more modern X-ray machinery.

We found it surprising that forensic odontologists who routinely undertake successful radiographic comparisons of teeth and dental restorations, performed poorly using essentially identical methods on a different body region. This suggests that training and experience must be directly applicable to the body region concerned. The poor performance generally observed for professional forensic anthropologists also indicated that osteology is not the single key factor to execute methods successfully even if the methods are heavily focused upon the radiographic appearance of bones. This stands to reason because radiographic comparisons are dependent upon interpretations of AM images that are a product of both soft and hard tissues.

Although the morphoscopic method described in this paper can be quickly conducted for single cases (<1 min), time remains a major disadvantage because it quickly accumulates for large arrays. This is particularly problematic in the JPAC context where thousands of AM radiographs might need to be searched without any supporting circumstantial information, and highlights the value for computer automated biometric approaches. On this front, we have already undertaken studies to pursue faster searches using the amplitude values calculated from elliptical Fourier functions that describe the outline shape of the clavicular shafts (41), and other computerized and more sophisticated approaches represent an ongoing area of research attention. Irrespectively, morphoscopic methods may hold value where other circumstantial or physical evidence provides an *a priori* short list of few potentially matching candidates (several to a few hundred individuals) and might act as the ultimate decider if computerized approaches only work to narrow large pools of individuals down to small groups of potential matches.

Acknowledgments

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