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Final Technical Report

Project Title:

Novel Computer-Assisted Identification Method Using Radiograph Comparison

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Abstract

Medical examiners and coroners (ME/C) hold statutory responsibility for the identification of medicolegal case decedents. DNA analysis, fingerprint comparison, dental comparison, and radiograph comparison are typical approaches to forensic identification. DNA analysis is affordable but has a turnaround time that is measured in weeks or months. The alternative methods have a reasonable turnaround time but there are other drawbacks, such as expense and lack of statistical validation.

In light of the 2009 National Academy of Sciences Report (1), which emphasizes the importance to the forensic sciences of a firm foundation in the scientific method, and the precedents set by court cases such as *Daubert* and *Kumho* (2-5), evidentiary standards for forensic evidence have become more stringent. Judicial inquiry regarding the admissibility of expert testimony places more emphasis on the reliability of the scientific method used by the expert (6). When there is a legal challenge to decedent identification, statistically validated methods are more likely to be admissible. In practice at the ME/C, increased statistical confidence in the identification method may reduce concerns regarding potential misidentification.

The computer-assisted radiograph comparison project has modified existing technology (QMA® software) to develop and test a quantitative method of radiographic identification for routine use in the ME/C that is accessible, time-sensitive, and relatively inexpensive. The method is targeted for fleshed adult decedents presenting to the ME/C with a suggested or tentative name and available radiographic records. Computer-Assisted Decedent Identification (CADI) utilizes the modified QMA® software program as the prototype of an automated forensic personal

identification tool. CADI analyzes the shapes of targeted skeletal elements imaged in standard radiographs and quantifies the likelihood that any two elements, and potentially the radiographs, are a “correct match”.

Over 54,000 radiograph comparisons were made during the development and testing of CADI. Revision of QMA® began with assessment of lateral cervical and lumbar spine radiographs to determine the optimal filters and match algorithms required to perform the automated analysis of skeletal element shape. Five image-processing filters (None, Histogram Equalization, Adaptive Histogram Equalization, North filter, Kalman Stack filter) and five image-match algorithms (Dice, Jaccard, Structural Similarity, Mutual Information, Matrix Correlation) were tested for their ability to delineate the shape characteristics of the vertebral body and generate the match score for a pair of radiographs (7-12). For the cervical region, the optimal filter and algorithm combination was a Histogram Equalization filter followed by the Jaccard algorithm similarity coefficient. For the lumbar region, the Adaptive Histogram Equalization filter was followed by the Jaccard algorithm similarity coefficient.

During validation testing, CADI analyzed age and sex specific test arrays that contained one “ID Pair” of radiographs imaged from the same individual at different points in time to simulate antemortem and postmortem radiographs. The test arrays were composed of the ID Pair and up to 30 radiographs from other individuals. CADI calculated match scores for all radiographs within the arrays. A 92-100% success rate was obtained for the correct match of the ID pair. When CADI chose the correct match, the calculated match score was approximately 15% higher than the match scores of the other radiographs included within the array.

Further development of CADI into a commercially available product will include validation of additional anatomical regions of interest commonly imaged for routine diagnosis

and treatment to increase the variety of antemortem radiographs available for assessment with CADI. Further, consensus regarding a statistical threshold for positive identification must be established based on the match scores of multiple skeletal elements from more than one region of the body and inclusion of prior probability in the statistical analysis.

Table of Contents

Abstract	2
Table of Contents	5
Executive Summary	6
I. Introduction	23
1. Statement of the Problem	23
2. Literature Review	25
3. Statement of Rationale for the Research	31
II. Methods	31
III. Results	35
1. Statement of Results	35
2. Forensic Expert Panel Web Conference	38
IV. Conclusions	40
1. Discussion of Findings	40
2. Implications for Policy and Practice	44
3. Implications for Further Research	46
References	48
Dissemination of Research Findings	53
Acknowledgements	53
Appendix A	54

Executive Summary

Introduction:

Medical examiners and coroners (ME/C) hold statutory responsibility for the identification of medicolegal decedents. The use of scientific identification is necessary in many cases where an adult decedent is tentatively identified, such as in homicide cases, decedents with disfiguring facial trauma or charring, and in cases of multiple fatalities where there is potential for incorrect assignment of identity. Further, in homicide cases successful prosecution of the alleged perpetrator may hinge on the presentation of a securely identified victim (13). Delay in the identification of a fleshed decedent with a tentative name may be confusing and frustrating to the family, and while awaiting identification, the decedent must be stored for a period of time under morgue refrigeration. Due to heavy ME/C caseloads in large offices, pervasive budget constraints, concern for delays experienced by the decedent's family, and storage issues, there is a need for identification methods that provide not only secure, but timely and cost-effective results. Figures obtained from Harris County Institute of Forensic Sciences (HCIFS) indicate that such a method targeting tentatively identified decedents would be an important resource for large ME/C offices.

HCIFS is located in Houston, Texas and serves a large urban-based county of an estimated four million residents (14). In 2011, the autopsy and external examination caseload of the HCIFS medical examiner service was 3,818. Of these cases, 1,101 decedents required scientific identification. Approximately 15% (576) of the total caseload were tentatively identified at check-in. These cases included fleshed but decomposed individuals, charred bodies,

commingled decedents from motor vehicle and airplane crashes, homeless individuals, and presumptive homicide cases.

HCIFS standard operating procedure requires a sequential process for scientific identification: fingerprint comparison by outside agencies; radiograph comparison by in-house anthropologists; dental comparison by the consulting odontologist; and DNA comparison by the in-house laboratory. The type of method used is both time and cost dependent. In 2011, 940 decedents were identified through fingerprints from Texas driver licenses or criminal records at no billed cost to HCIFS. The turnaround time was a few hours to approximately two days. Twenty four decedents were identified by in-house anthropologists within hours at no additional cost to HCIFS. Fifty-seven were identified by odontologic examination at a total consultant cost of \$24,000 and a turnaround time of one to three days. Finally, 74 decedents were identified through DNA profile comparison at an estimated internal cost of \$4,440, and with a routine time delay of 15-60 days from submission of the sample. ME/C offices without an on-site DNA laboratory are likely to experience a longer turnaround interval for DNA results due to the large number of cases analyzed by centralized, accredited forensic DNA laboratories. External DNA analysis, previously expensive but currently offered at no charge through the President's DNA Initiative (15), has a turnaround time historically measured in months.

Literature Review:

Establishing medicolegal decedent identity typically relies on DNA, dental comparison, or fingerprints. However, a family reference sample may not be available for comparison. Lack of antemortem dental care and/or records may preclude the analysis of dental characteristics. Fingerprinting may not be possible when the hands are in an advanced stage of decomposition,

traumatized, or scavenged by carnivores, and many individuals do not have fingerprints on record. When computerized fingerprint comparison through the Automated Fingerprint Identification System (AFIS) is unsuccessful, latent examination by an analyst may be requested if there are latent fingerprints available for comparison. However, recent research suggests that cognitive or confirmation bias may play a role and adversely affect the comparison of dental radiographs and latent fingerprint comparisons, which may lead to evidentiary challenges (16-20).

When DNA, dental comparison, and fingerprint analysis are unsuccessful, the ME/C may request radiographic comparison of skeletal elements conducted by an analyst with specialized training, such as a forensic anthropologist, a forensic radiologist, or a forensic pathologist (21). The specialist typically undertakes identification analysis by qualitative comparison of skeletal elements in antemortem and postmortem radiographs, evaluating the radiographs for evidence of consistencies and inconsistencies in the anatomic regions depicted. The points of comparison include bone shape, size and condition, trabecular patterns, and signatures of the subject's life history such as the presence of pathological conditions or antemortem trauma, bony stress markers, and orthopedic devices. The method has a long history spanning multiple scientific disciplines (radiology, pathology, dentistry, anthropology) and is widely accepted, even though it may be subject to analyst confirmation bias for the same reasons documented for dental and latent fingerprint examinations (16-20).

A standardized protocol has not been accepted by the scientific community that delineates the optimum features, requisite number of points of comparison, or the quantification of consistencies that are needed to support a positive identification through radiograph comparison. Development of quantifiable, validated, and replicable methods of identification

that can be selected for use based on the available evidence and the circumstances of the individual medicolegal case is crucial given the admissibility criteria for expert testimony established in Supreme Court cases. Three Supreme Court decisions set the legal standard for the assessment of the admissibility of expert testimony: *Daubert v. Merrell Dow Pharmaceuticals, Inc.* (1993), *General Electric Co. v. Joiner* (1997), and *Kumho Tire and Co. v. Carmichael* (1999) (2-5). For a succinct explanation of each of these cases see Christensen and Crowder (22).

Subsequent to the precedents set by *Daubert*, *Joiner*, and *Kumho*, practitioner experience level remains important in the interpretation of analytical results. However, questions of validity may arise when a scientific method relies on a non-objective foundation. Published literature on identification through radiograph comparison indicates that although there is general peer acceptance of the methodology, there is a lack of confidence that identifications performed using traditional radiograph comparison will be admissible in court in light of the recent revisions of admissibility standards (5, 23). Similar to fingerprint and bite mark assessment, there is no accepted minimum number of matching points necessary for a positive identification by radiograph comparison (24), with recommendations varying from a single unique characteristic, two uncommon features), and at least four points of correspondence (21-27). In this regard, the novel computer-assisted identification method developed through this project has the ability to test multiple skeletal elements within an anatomic region to provide increased statistical support for the results of the comparison. The project builds on previous work that demarcates a quantified accuracy and precision rate in radiograph comparison that has the potential to meet the standards of admissibility for expert court testimony.

Statement of Rationale for the Research:

The primary objective of the project funded by the National Institute of Justice (NIJ) entitled “Novel Computer-Assisted Identification Method Using Radiograph Comparison” was to revise existing cutting-edge technology utilized in the clinical setting into a new quantitative method of radiographic identification that could be used routinely in the ME/C office. The method is proposed for use with fresh, skeletally articulated, fleshed decedents and is designed to meet federal guidelines for admissibility of evidence. Additional benefits of the relatively inexpensive method are the planned accessibility and timeliness of results. The secondary objective of the project was to promote interdisciplinary collaboration in the development of new forensic methodologies. Researchers outside the fields of forensic sciences can contribute the knowledge and expertise garnered from other disciplines, such as biomedical and software engineering, to enhance the strength of the proposed forensic method.

Methods

The foundation of the CADI method is the revised forensic version of “Quantitative Motion Analysis” software (QMA®, created and developed by Medical Metrics, Incorporated [MMI], Houston, Texas). QMA® has been validated in multiple studies (28-31) and used in over 100 peer-reviewed studies of spinal biomechanics and spinal treatments (reference list available on request). QMA® allows for computer-assisted matching of specific objects that can be seen in multiple images. It has most commonly been used in orthopedic diagnosis and treatment to measure motion between vertebrae and identify changes in spatial relationships between vertebrae over time. The software tracks a specific object between multiple radiographic images. This is a fundamental feature of CADI that facilitates determination of whether a specific anatomical feature is a match as imaged in radiographs taken at different time periods.

The initial phases of CADI development began with a time-intensive assessment of neutral-lateral cervical and lumbar spine radiographs, previously archived at MMI from a clinical trial of spine treatments, to determine the optimal filters and match algorithms required to perform the automated analysis of skeletal element shape. These images of male or female individuals aged 40-69 years are representative of typical clinical radiographs that might be used for a decedent identification case. Although the age range is limited by the archived radiographs, 53% of medicolegal decedents presenting to HCIFS in 2011 with a tentative name were 40 years and older (305/576). The radiographs were reviewed for artifacts, excessive noise, poor contrast, obstruction, or out-of-plane artifacts that could confound the analysis and might eliminate the radiograph from use in an actual decedent identification case. Radiographs of subjects with severe osteophytic growth between scans were also excluded.

Custom codes were written to perform the image processing and generate similarity metrics using MATLAB (Mathworks, Natick, MA). The images were spatially stabilized and scaled by CADI so that the regions of interest (ROI) were of the same apparent size. The images were extracted and pre-processed to adjust intensity, correct for streak artifacts, reduce noise, and reduce the image resolution, based on prior experience with feature identification in spine radiographs using QMA®. A polygon region of interest around the vertebral body was manually defined to mask out everything but the target vertebral body.

Each test array during the development phase was comprised of one ID pair and 10 comparison images. The ID pair included an early time point radiograph (simulating antemortem), and a radiograph taken two to three years later (simulating postmortem) from the same individual. To construct an array, the ID pair was combined with radiographs from 10 different individuals (one radiograph per individual) and used to represent a pool of other

possible antemortem radiographs from the same sex and age cohort. Thus, each test array consisted of one correct match and 10 incorrect matches.

Five image-processing filters and five match algorithms were tested for their ability to delineate the shape characteristics of the vertebral body and generate the similarity metric, or the “match score”, for a pair of registered radiographs. For each array, a match score between the postmortem and the antemortem image of the ID pair and all comparison radiographs in the array was calculated. Each combination of image-processing filter and match score algorithm was tested. Match scores were statistically analyzed using Stata (StataCorp, College Station, TX).

For each combination of a preprocessing filter and match score algorithm, the percentage of comparisons correctly classified as a “correct” or “incorrect” pair was computed using effect size (average match score for correct matches minus match score for incorrect matches, divided by the standard deviation for all match scores) and receiver-operator-curve (ROC) analysis. The optimal combination of image processing filter and match score algorithm was determined from the pooled comparisons.

Once the optimal filters and algorithms were identified, the project moved forward with further coding revision of QMA® into the CADI software prototype and validation of the software for lateral views of the cervical and lumbar anatomical regions. In order to validate the CADI prototype, multiple test scenarios were executed using cervical and lumbar spine radiographs from the MMI-archived database and the second National Health and Nutrition Examination Survey, NHANES II, which is a nation-wide sample of 27,801 people (32). Over 54,000 radiograph comparisons were made during development and testing of the method.

For the validation testing phase, radiograph cases were randomly selected for each test array based on age and sex, using only cases that had two neutral-lateral radiographs of the

cervical spine taken at least two years apart. Multiple age and sex specific arrays containing 5-30 images and at least one ID Pair were assembled. Age and sex specific test arrays were also analyzed for combined C3-C5 elements and combined L1-L5 elements.

Results

Statement of Results:

Six validation tests were conducted. In Test 1, age and sex specific arrays were created using radiographs compiled from two separate clinical studies in order to analyze match scores separately by sex, age, and then sex and age combined. Within each age and sex specific group the influence of individual vertebral level on the correct classification of radiographs was also tested. In total, individual cervical vertebrae were correctly classified in 98.44% of males and 98.86% of females. Individual lumbar vertebrae were correctly classified in 94.08% of males, and 93.21% of females.

In Test 2, the influence of array size on correct classification was investigated using the male, 40-44 years, C3 level Test Array from Test 1. Test 2 included five ID pairs and a varying number of radiographs from different individuals (5-30 radiographs in increments of 5). All radiographs (100%) were correctly classified in this test regardless of the array size.

The importance of non-age specific test arrays on correct classification was determined by Test 3. Two radiographs from different male individuals were randomly selected from each of the six age groups. The 12 radiographs formed a base array that spanned the entire age range from 40-69 years. One ID pair from each age group was added to the base array independently, forming six final test arrays. All radiographs (100%) were correctly classified in Test 3.

Table 1. The influence of sex, cervical vertebra level or age and sex on CADI classification of correct matches

Age range	Sex	Cervical Vertebral level	# of vertebral level-specific arrays	# of ID pairs	% correctly classified
Overall					
All age-ranges combined	Male and Female combined	C3, C4, C5 combined	83	23 to 31	98.69
Sex-specific					
All age-ranges combined	Male	C3, C4, C5 combined	48	14 to 18	98.44
All age-ranges combined	Female	C3, C4, C5 combined	35	9 to 13	98.86
Vertebral level-specific					
All age-ranges combined	Male and Female combined	C3	31	31	98.83
All age-ranges combined	Male and Female combined	C4	29	29	99.37
All age-ranges combined	Male and Female combined	C5	23	23	98.02
Age- and sex-specific					
40-44 years	Male	C3, C4, C5 combined	11	3 to 5	99.17
45-49 years	Male	C3, C4, C5 combined	9	3	100
50-54 years	Male	C3, C4, C5 combined	9	3	100
55-59 years	Male	C3, C4, C5 combined	9	3	94.95
60-64 years	Male	C3, C4, C5 combined	8	2 to 3	100
65-69 years	Male	C3, C4 combined	2	1	100
40-44 years	Female	C3, C4, C5 combined	7	1 to 3	98.70
45-49 years	Female	C3, C4, C5 combined	9	3	100
50-54 years	Female	C3, C4, C5 combined	6	2	100
55-59 years	Female	C3, C4, C5 combined	9	3	97.98
60-64 years	Female	C3, C4 combined	2	1	100
65-69 years	Female	C3, C4 combined	2	1	100

Test 4 examined the repeatability and reliability of the tracking process using QMA® and the masking performed by the analyst. Radiographs for the male, 40-44 years, C3 level Test Array from Test 1 were preprocessed (stabilization and masking) and re-tested on two separate occasions. All radiographs (100%) were correctly classified in both events of Test 4.

Test 5 found that varying the pool of comparison images did not affect correct classification of radiographs. All of the radiographs (100%) were correctly classified using two test arrays with different individual radiographs compared to the same ID pair.

Table 2. The influence of sex, lumbar vertebra level or age and sex on CADI classification of correct matches

Age range	Sex	Lumbar Vertebral level	# of vertebral level-specific arrays	# of ID pairs	% correctly classified
Overall					
All age-ranges combined	Male and Female combined	L1, L2, L3, L4, L5 combined	192	46	93.61
Sex-specific					
All age-ranges combined	Male	L1, L2, L3, L4, L5 combined	109	27	94.08
All age-ranges combined	Female	L1, L2, L3, L4, L5 combined	83	19	93.21
Vertebral level-specific					
All age-ranges combined	Male and Female combined	L1	37	37	93.61
All age-ranges combined	Male and Female combined	L2	45	45	93.94
All age-ranges combined	Male and Female combined	L3	45	45	92.93
All age-ranges combined	Male and Female combined	L4	45	45	94.14
All age-ranges combined	Male and Female combined	L5	20	20	95.45
Age- and sex-specific					
40-44 years	Male	L1, L2, L3, L4, L5 combined	9	3	98.99
45-49 years	Male	L1, L2, L3, L4, L5 combined	15	5	95.15
50-54 years	Male	L1, L2, L3, L4, L5 combined	24	6	95.08
55-59 years	Male	L1, L2, L3, L4, L5 combined	30	6	93.64
60-64 years	Male	L1, L2, L3, L4, L5 combined	25	5	93.09
65-69 years	Male	L1, L2, L3, L4, L5 combined	6	2	95.45
40-44 years	Female	L1, L2, L3, L4, L5 combined	8	2	92.05
45-49 years	Female	L1, L2, L3, L4, L5 combined	8	2	96.59
50-54 years	Female	L1, L2, L3, L4, L5 combined	10	2	96.36
55-59 years	Female	L1, L2, L3, L4, L5 combined	12	3	93.94
60-64 years	Female	L1, L2, L3, L4, L5 combined	20	5	93.18
65-69 years	Female	L1, L2, L3, L4, L5 combined	25	5	92.73

Test 6 determined whether multiple correct matches could be identified in a single test array. An age and sex specific test array was created with five ID pairs and five incorrect match radiographs. Thus, each of the five ID pairs was tested against nine incorrect match radiographs. All five of the ID pairs (100%) were correctly matched.

In summary, the CADI cervical vertebrae results ranged from 95-100% of the ID pairs correctly matched. The CADI lumbar results ranged from 92-99% of the ID pairs correctly matched. Following compilation of the CADI cervical and lumbar vertebrae results, a brief comparison of CADI accuracy with traditional anthropologic radiograph comparison was

performed. Six forensic anthropologists encompassing a range of years of radiograph comparison experience assessed 27 test arrays for which CADI had reported the correct match for the cervical vertebrae bodies. The anthropologists were allowed to use all morphological features observed in the lateral radiographs of the cervical spine. The anthropologists' results ranged from 88.88% to 100% of the ID pairs correctly identified, slightly lower than the results generated by CADI for the bodies only.

Forensic Expert Panel Web Conference:

A description of the CADI method and the results of the validation testing were disseminated to a panel of four forensic experts through a Power Point presentation in June 2013. The panel was comprised of three forensic anthropologists (two with ME/C experience and one with military decedent recovery experience) and one practicing medical examiner whose sub-specialty is radiology. A set of discussion questions (Appendix A) were provided to the panel for their feedback on the method in terms of the level of scientific acceptability and the efficacy of the CADI approach for routine use in identification. The panel then joined the principal investigator, co-investigators, and the project postdoctoral fellow in a web conference version of a round table discussion.

The panel requested clarification on stabilization of images, match scores, thresholds for a match, sample size, the limitations of the method, and the practical application of the software. These issues were further explained by the HCIFS and MMI researchers and the panel members regarded the explanations to be satisfactory. At least two of the members are of the opinion that quantitative results for anthropologic methods of identification are crucial. One member stated

that “the concept is exciting and it is apparent that the researchers have put a lot of thought into the development process”. The panel listed the following as strengths of the method:

- Statistical probabilities can be assigned to an antemortem/postmortem radiograph image comparison.
- CADI is able to remove size and orientation as factors in the comparison.
- The CADI developers are aware of the questions that forensic scientists want answered in the quantification of identification methods.

The following were noted as potential weaknesses of the method:

- CADI cannot currently determine a non-match because a statistical threshold for a correct match has not been developed.
- The actual cost and turnaround time are not yet identified. If the method is not cost-efficient or the turnaround time is too long, it will not be an improvement over the current methods of choice.

Conclusions

Discussion of Findings:

The results of the validation testing show that CADI can choose the ID pair as the correct match 95-100% of the time when assessing radiographs of the lateral cervical vertebrae. CADI can choose the correct match 92-99% of the time when assessing the relatively uniform shapes of the lateral lumbar vertebrae bodies. Use of the software program greatly reduces analyst subjectivity and the CADI prototype is equipped with an analyst-friendly interface. Results

generated by CADI are quantitative and replicable. The preliminary findings are quite promising but further development and testing of the method is necessary.

There are substantial challenges in statistical interpretation of the CADI method and results that have been recognized but not yet solved. One important challenge is that the software calculates a match score for all comparisons, correct and incorrect matches, in a test array. Two pathways have been considered to address this challenge (verification or identification). One verification option is to calculate a match score for a large number of correct and incorrectly matched radiographs and identify the magnitude of match score that is optimally sensitive and specific (33). Match scores above the threshold would support a certain probability of a correct match. A drawback to that option is that the results of the validation tests should only be used if the type of radiograph (e.g., lateral cervical, AP chest, AP pelvis, hip, etc.) and quality of the radiograph from the actual case is equivalent to the type and quality of radiographs in the verification. In this verification scenario, the result of the test would be “verified” or “not verified”, with the definition of “verified “ requiring a full understanding of the validation experiment that was used to establish the threshold. The project investigators decided not to pursue this option.

Another verification solution to the challenge is to use normalized match scores. The highest match score is set to 100 and all others normalized to that. If CADI is successful, the correct match will have the highest match score, and all match scores for non-matching images will be substantially less. After normalization, it is desirable to have a large gap between the normalized score for the correct match (which should be close to 100), and all other match scores (which should be much less than 100). The probability that a correct match has been found can be based on validation experiments to determine a threshold level of difference between

normalized match scores. A limitation of this approach is that the probabilities are directly relevant only to the specific imaging used in the validation tests. It may be necessary to have different thresholds for each type of radiograph that might be used, and for each unique anatomic feature. That would be determined by completing appropriate validation experiments.

An alternative approach is to use CADI for identification as described above, rather than for verification. In that scenario, statistics can be based on the probability of picking a radiograph from a collection of radiographs by chance. That approach is analogous to a conventional police line-up. CADI, as currently validated, has been used to test one anatomic feature at a time (e.g., the 3rd cervical vertebral body). CADI can be performed on multiple anatomic features seen in a radiograph (e.g., the 3rd, 4th, 5th, and 6th vertebral bodies). That would be analogous to an expert studying multiple different anatomic features in the comparison radiographs. However, it is a challenge to use results from multiple testing of multiple anatomic features to improve confidence that a correct match has, or has not been, found. The simplest approach is to recognize that if an anatomic feature in a postmortem radiograph is compared to the same feature in a collection of 11 radiographs (one of which may be a correct match), the probability of picking, by chance, the correct match from the 11 radiographs is 1 in 11. If a different anatomic feature is then tested, using the same collection of radiographs, the probability of picking, by chance, the correct match from the 11 radiographs is again 1 in 11. The nominal probability of picking, by chance, the correct match in both tests is $1/11 * 1/11 = 1/121$. This process can be repeated for multiple features, with the probability becoming smaller with each feature analyzed. In addition, the number of known incorrectly matched radiographs can be increased. For example, if a collection of 50 radiographs is used and 5 features tested, and the CADI test picks

the correct match in each test, then the nominal probability that the radiograph was selected by chance is: $1/50 \times 1/50 \times 1/50 \times 1/50 \times 1/50 = 1/312,500,000$.

It can be argued that a correction must be added since repeated tests are being performed on the same set of radiographs. That issue could potentially be mitigated by using a unique collection of unmatched radiographs for each anatomic feature tested.

When used for verification or for identification, a computer-assisted radiographic method would ideally account for the prior probability that a forensics team could have found a matching antemortem radiograph within the community that they serve. Use of the prior probability can dramatically improve the reliability of a test, much as it does in a conventional police line-up, where there is a 1 in 5 chance that a perpetrator could be identified by chance alone, but the chance-probability of a perpetrator being found by police in the community where the crime occurred at about the time the crime occurred, and etc., is assumed to be very low. Based on the perceived (but largely untested) importance of the prior probability combined with the identification in a small line-up, the conventional police line-up is generally accepted.

Implications for Policy and Practice

The primary outcome measures of the project are the validated prototype of the forensic identification software developed from the revision of QMA® and construction of a model for future implementation in ME/C offices in which ME/C staff will be able to use an in-house computer workstation (node) to send radiograph data into a system monitored by trained analysts (Figure 2).

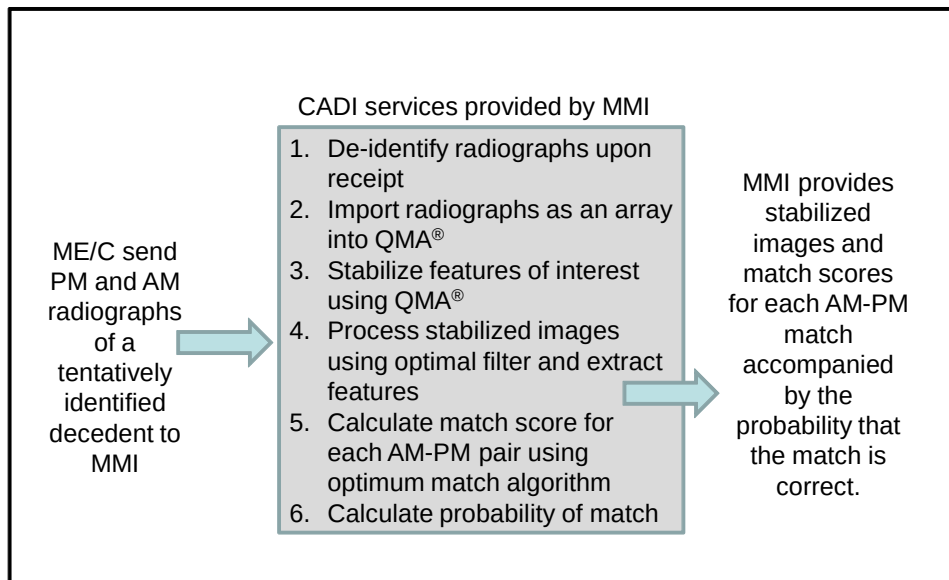


Figure 2. The Future CADI Model

Implications for Further Research:

In order to use CADI as a secure, quantitative method for identification, additional statistical research should be conducted as described under the Discussion section. CADI has the ability to test multiple skeletal elements to provide increased statistical support for the results of the comparison but the quantification of this feature must be rigorously tested.

Testing of CADI using actual ME/C case work and additional anatomic regions of interest including the pelvis, hands, chest, and frontal sinuses are vital to statistical confidence in the method. A pilot project to test the usefulness of a computer “node” installed at participating ME/C offices to provide ME/C access to trained CADI analysts for radiograph comparison results is proposed. The node concept and its potential for national implementation will be first evaluated on medicolegal casework at HCIFS. Data regarding accuracy and ease of use will be collected for each CADI node use. The results of the comparisons will not be used for official identification of remains until the method has been further validated using postmortem images.

A cost/benefit analysis will also be performed based on the actual costs of submitting CADI to external trained analysts. The costs of developing the software into a stand-alone program that could be purchased for internal ME/C use will be explored. With positive results, a plan for installation and testing of nodes at other large ME/C offices will be developed and implemented.

INTRODUCTION

Statement of the Problem:

Medical examiners and coroners (ME/C) hold statutory responsibility for the identification of medicolegal decedents. According to the 2004 Bureau of Justice Statistics, ME/C in the United States process approximately 4,400 unidentified human decedents a year and nearly a quarter remain unidentified after one year (34). Additionally, the Bureau estimates that 13,500 unidentified human decedents are on record, with 40% of those decedents archived in ME/C offices indefinitely. With the inception and continued development of NamUs (National Missing Persons Data System), these figures are likely being reduced. However, the need for timely scientific identification extends beyond the medicolegal decedent presenting as a complete unknown. Scientific identification is necessary in many cases where an adult decedent is tentatively identified, such as in homicide cases, decedents with disfiguring facial trauma or charring, and in cases of multiple fatalities where there is potential for incorrect assignment of identity. Further, in homicide cases successful prosecution of the alleged perpetrator may hinge on the presentation of a securely identified victim. (13). Delay in the identification of a fleshed decedent with a tentative name may be confusing and frustrating to the family, and while awaiting identification, the decomposing decedent must be stored for a period of time under morgue refrigeration. Due to heavy ME/C caseloads in large offices, pervasive budget constraints, concern for delays experienced by the decedent's family, and storage issues, there is a need for identification methods that provide not only secure, but timely and cost-effective results. Figures obtained from Harris County Institute of Forensic Sciences (HCIFS) indicate that

such a method targeting tentatively identified decedents would be an important resource for large ME/C offices.

HCIFS is located in Houston, Texas and serves a large urban-based county of 1,703 square miles with an estimated four million residents (14). In 2011, the autopsy and external examination caseload of the HCIFS medical examiner service was 3,818. Of these cases, 1,101 decedents required scientific identification. Approximately 15% (576) of the total caseload were tentatively identified at check-in. These cases included fleshed but decomposed individuals, charred bodies, commingled decedents from motor vehicle and airplane crashes, homeless individuals, and presumptive homicide cases.

HCIFS standard operating procedure requires a sequential process for scientific identification: fingerprint comparison by outside agencies; radiograph comparison by in-house anthropologists; dental comparison by the consulting odontologist; and DNA comparison by the in-house laboratory. The type of method used is both time and cost dependent. In 2011, 940 decedents were identified through fingerprints from Texas driver licenses or criminal records at no billed cost to HCIFS. The turnaround time was a few hours to approximately two days. Twenty four decedents were identified by in-house anthropologists within hours at no additional cost to HCIFS. Fifty-seven were identified by odontologic examination at a total consultant cost of \$24,000 and a turnaround time of one to three days. Finally, 74 decedents were identified through DNA profile comparison at an estimated internal cost of \$4,440, and with a routine time delay of 15-60 days from submission of the sample. ME/C offices without an on-site DNA laboratory are likely to experience a longer turnaround interval for DNA results due to the large number of cases analyzed by centralized, accredited forensic DNA laboratories. External DNA

analysis, previously expensive but currently offered at no charge through the President's DNA Initiative (15), has a turnaround time historically measured in months.

Literature Review:

Establishing medicolegal decedent identity typically relies on DNA, dental comparison, or fingerprints. However, a family reference sample may not be available for comparison. Lack of antemortem dental care and/or records may preclude the analysis of dental characteristics. Fingerprinting may not be possible when the hands are in an advanced stage of decomposition, traumatized, or scavenged by carnivores, and many individuals do not have fingerprints on record. When computerized fingerprint comparison through the Automated Fingerprint Identification System (AFIS) is unsuccessful, latent examination by an analyst may be requested if there are latent fingerprints available for comparison. However, recent research suggests that cognitive or confirmation bias may play a role and adversely affect the comparison of dental radiographs and latent fingerprint comparisons, which may lead to evidentiary challenges (16-20).

When DNA, dental comparison, and fingerprint analysis are unsuccessful, the ME/C may request radiographic comparison of skeletal elements conducted by an analyst with specialized training, such as a forensic anthropologist, a forensic radiologist, or a forensic pathologist (21). Radiograph identification, performed through a point-by-point comparison between similar antemortem views of a missing person and postmortem views of a decedent, is a non-destructive method that does not expose the practitioner to biohazards beyond routine manipulation of the body. The analyst typically undertakes identification analysis by qualitative comparison of skeletal elements in antemortem and postmortem radiographs, evaluating the radiographs for

evidence of consistencies and inconsistencies in the anatomic regions depicted. The points of comparison include bone shape, size and condition, trabecular patterns, and signatures of the subject's life history such as the presence of pathological conditions or antemortem trauma, bony stress markers, and orthopedic devices. The method has a long history and is widely accepted, even though it may be subject to analyst confirmation bias for the same reasons documented for dental and latent fingerprint examinations.

As early as 1964 a Canadian author, W.J. Deadman (35), opined that radiograph comparison may be used successfully in concert with other forensic methods to identify human remains that have been damaged by burning or decomposition. He suggested that the forensic pathologist document "peculiarities" of the skeletal system through radiographic means for comparison with the records of missing persons. Sanders et al. (36) published an article in the radiological literature in 1972 in which they state that radiology may be used to identify medicolegal decedents when other means of identification are not available. In 1977, Martel et al. (37) describe the use of radiographic identification methods by the forensic pathologist. From the late 1980s-1990s, forensic anthropologists, among others, have published multiple articles and case studies supporting the use of radiograph comparison for identification. (See references 38-46 for a sampling of these publications).

Measurement of the frontal sinuses as a tool for personal identification was explored by de Ribeiro in 2000 (47). In 2001 Riepert, et al. proposed radiographic image comparison of the skulls of deceased individuals as a method of forensic identification (48). The authors found that certain features could be measured and compared even when the skull was imaged in different positions, and called for additional research in digital radiograph comparison as well as quantification of methods for presentation in court. A paper by Kirk et al., in 2002 (49) reported

the results of their frontal sinus comparison validation study. The authors state that they made 35 conclusive postmortem to antemortem qualitative frontal sinus matches, sixteen of which were also matched by measurements of the sinuses.

Christensen (23) tested the reliability of frontal sinuses in positive identification and reported the use of Elliptic Fourier Analysis (EFA) coefficient comparison in estimating the probability of a correct identification to be a reliable technique. She thus recommended EFA comparison of frontal sinuses as a quantified form of substantiation in forensic identification (23). Her study obtained outlines for comparison “by superimposing each original radiograph with tracing paper, and tracing the frontal sinus outline onto the paper over a light table” (23).

More recently Shamir, et al, with funding support from the National Institutes of Health, used 1,275 radiographic images in 20 repeated experiments to show that individuals can be identified by comparison of knee joint radiographs (50). The recognition accuracy of the knee joint was statistically higher than random but became less accurate as the number of individuals in the dataset increased. These results support the inclusion of more than one anatomic region in a radiograph comparison analysis, and interpretation of the range of variability seen in the raw match scores for target anatomic features.

There have also been several published case reports that utilized antemortem and postmortem chest radiographs to aid in the identification of decomposed/damaged remains and disarticulated postcranial skeletons (51-57). Stephan and co-authors (51) examined antemortem and postmortem chest radiographs focusing on the clavulae and vertebrae to identify skeletons of missing U.S. soldiers from past military operations. The authors reported that chest radiographs are valuable for the identification of disarticulated skeletons when assessed by

trained examiners and that the study highlights “the sufficiency for identification decisions to be based on chest radiographs displaying normal skeletal morphologies” (51).

Rogers and Allard (24) predicated that “A mathematical means of arriving at a positive identification ensures replicability, makes criteria explicit, and provides a method that can be debated and discussed”. Biometric analysis is the basis of DNA identification, dental radiograph comparison, fingerprint comparison and facial recognition, among other major methodologies used routinely in the forensic sciences (33,58-61). Work by van der Meer and colleagues incorporated digital subtraction radiography (ImageTool v3.0 with UT-ID plugin, University of Texas Health Science Center, San Antonio, Texas) to test a potential means of automated dental comparison. Advances in biometric technology have also been explored in other fields. One such application is the use of radiograph comparison to improve the efficiency of hospital medical record storage. Picture Archiving and Communication System (PACS) is widely used in major hospital networks (60-62). PACS servers can hold a large quantity of digital images but if a radiograph is misfiled, it is difficult to retrieve and may be lost indefinitely in the system, or worse, used in the treatment of a different patient. Radiologists and hospital administrators have published a number of recent articles reporting successful use of digital radiograph patient matching to prevent these errors. Morishita and colleagues, in their work with chest radiographs, described the method as a form of “biological fingerprint” (62). The majority of this work was based on edge-detection and edge-enhancement, with computer-assisted overlay of comparison images to match up the outlines.

Although the literature in support of radiograph comparison for personal identification is plentiful, a standardized protocol for radiograph identification that delineates the optimum features and requisite number of points of comparison, or quantifies an error rate for a positive or

negative identification has not been accepted by the scientific community. For example, consistency in the shape of the frontal sinuses in an antemortem and postmortem radiograph is commonly applied as a basis for positive identification (23, 47, 49). However, the actual individuality of that shape in and between populations has not been adequately tested or quantified, nor has the effect that a small deviation in position may have on the shape as seen by the analyst. Riepert and colleagues discovered in their computer-assisted radiograph comparison study of cranial traits that a significant amount of variation observed in the frontal sinus shape was the result of skull positioning during imaging and not sinus structure (48).

Given the admissibility criteria for expert testimony established in Supreme Court cases, developing quantified, validated, and replicable methods of identification that may be selected for use based on the circumstances of the individual medicolegal case has become a matter of importance for ME/C. Three Supreme Court decisions set the legal standard for the assessment of the admissibility of expert testimony: *Daubert v. Merrell Dow Pharmaceuticals, Inc.* (1993), *General Electric Co. v. Joiner* (1997), and *Kumho Tire and Co. v. Carmichael* (1999) (2-5). For a succinct explanation of each of these cases see Christensen and Crowder (22).

The Daubert ruling provides general guidelines to assist trial judges in the evaluation of scientific or technical testimony that instructs the judge to concentrate on theory and methodology rather than on the conclusions produced (22). The guidelines include the assessment of whether the theory or technique has been tested, there is a known rate of error, there are standards for application of the method, the method has been subject to peer review and publication, and whether “the theory or technique has been generally accepted within the relevant scientific community”(22).

The latter two court cases supplement and clarify the Daubert decision. The Joiner ruling “questions whether existing scientific evidence can be generalized to address specific causal relationships” (16) and, contrary to Daubert, argued that methods and conclusions are associated. Thus, according to *Joiner*, “an expert’s conclusion should be excluded in the event that valid reasoning does not support it” (22). Finally, the Kumho decision conveyed the flexibility of the Daubert guidelines, outlining that not all of the Daubert criteria may be relevant to the expert testimony. Kumho also delineated the assessment of all expert testimony, not just scientific testimony.

Subsequent to the precedents set by Daubert, Joiner, and Kumho, practitioner experience level remains important in the interpretation of analytical results. However, questions of validity may arise when a scientific method relies on a non-objective foundation. Published literature on identification through radiograph comparison indicates that although there is general peer acceptance of the methodology, there is a lack of confidence that identifications performed using traditional radiograph comparison will be admissible in court in light of the recent revisions of admissibility standards (5, 22). Similar to fingerprint and bite mark assessment, there is no accepted minimum number of matching points necessary for a positive identification by radiograph comparison (24), with recommendations varying from a single unique characteristic, two uncommon features), and at least four points of correspondence (21-27).

In light of a recent survey of state court judges where 91% of those surveyed indicated quantified error rates to be useful in their assessment of the quality of presented scientific evidence (63), radiograph comparison as an identification method is also in danger of becoming inadmissible in local courts.

Statement of Rationale for the Research:

The primary objective of the project funded by the National Institute of Justice (NIJ) entitled “Novel Computer-Assisted Identification Method Using Radiograph Comparison” was to revise existing cutting-edge technology utilized in the clinical setting into a quantitative method of radiographic identification for routine use in the ME/C office. The method is proposed for use with fresh, skeletally articulated, fleshed decedents and is designed to meet federal guidelines for admissibility of evidence. Additional benefits of the relatively inexpensive method are the planned accessibility and timeliness of results. The secondary objective of the project was to promote interdisciplinary collaboration to initiate the transformation of radiograph comparison identification from a subjective, experience-based method to an objective method validated through statistical analysis.

Methods

The foundation of the Computer-Assisted Decedent Identification method (CADI) is the revised forensic version of “Quantitative Motion Analysis” software (QMA®, created and developed by Medical Metrics, Incorporated [MMI], Houston, Texas). QMA® has been validated in multiple studies (29-32) and used in over 100 peer-reviewed studies of spinal biomechanics and spinal treatments (reference list available on request). QMA® allows for computer-assisted matching of specific objects that can be seen in multiple images. It has most commonly been used in orthopedic diagnosis and treatment to measure motion between vertebrae and identify changes in spatial relationships between vertebrae over time. The software tracks a specific object between multiple radiographic images. This is a fundamental feature of

CADI that facilitates determination of whether a specific anatomical feature is a match as imaged in radiographs taken at different time periods.

The initial phases of CADI development began with a time-intensive assessment of neutral-lateral cervical and lumbar spine radiographs, previously archived at MMI from a clinical trial of spine treatments, to determine the optimal filters and match algorithms required to perform the automated analysis of skeletal element shape. These images of male or female individuals aged 40-69 years are representative of typical clinical radiographs that might be used for a decedent identification case. Although the age range is limited by the archived radiographs, 53% of medicolegal decedents presenting to HCIFS in 2011 with a tentative name were 40 years and older (305/576). The radiographs were reviewed for artifacts, excessive noise, poor contrast, obstruction, or out-of-plane artifacts that could confound the analysis and might eliminate the radiograph from use in an actual decedent identification case. Radiographs of subjects with severe osteophytic growth between scans were also excluded so as to increase the difficulty of the match.

Custom codes were written to perform the image processing and generate similarity metrics using MATLAB (Mathworks, Natick, MA). The images were spatially stabilized and scaled by CADI so that the regions of interest (ROI) were of the same apparent size. The images were extracted and pre-processed to adjust intensity, correct for streak artifacts, reduce noise, and reduce the image resolution, based on prior experience with feature identification in spine radiographs. A polygon region of interest around the vertebral body was manually defined to mask out everything but the target vertebral body.

Each test array during the development phase was comprised of one ID pair and 10 comparison images (Figure 1). The ID pair included an early time point radiograph (simulating antemortem),

and a radiograph taken two to three years later (simulating postmortem) from the same individual. To construct an array, the ID pair was combined with radiographs from 10 different individuals (one radiograph per individual) and used to represent a pool of other possible antemortem radiographs from the same sex and age cohort. Thus, each test array consisted of one correct match and 10 incorrect matches.

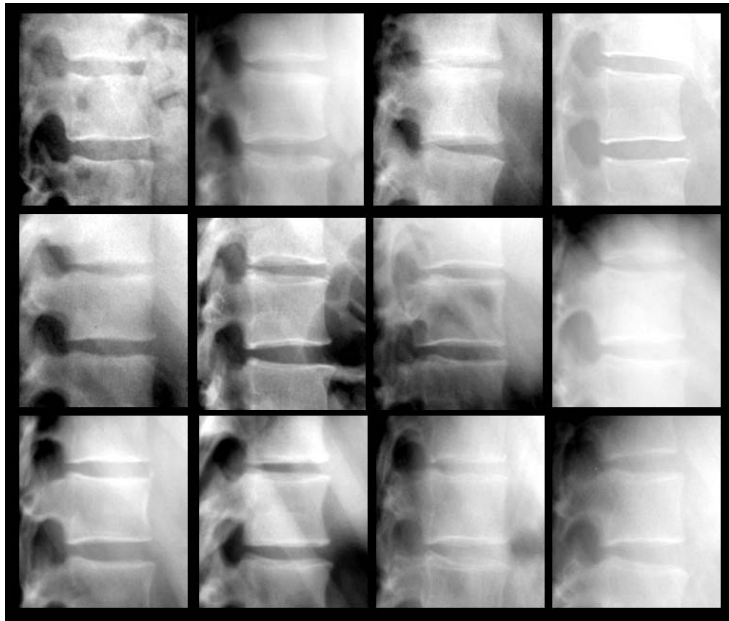


Figure 1. Radiograph Array (12) of Stabilized Lumbar Vertebrae – Project Development Phase

Five image-processing filters and five match algorithms were tested for their ability to delineate the shape characteristics of the vertebral body and generate the similarity metric, or the “match score”, for a pair of registered radiographs. For each array, a match score between the postmortem and the antemortem image of the ID pair and all comparison radiographs in the array was calculated. Each combination of image-processing filter and match score algorithm was tested. Match scores were statistically analyzed using Stata (StataCorp, College Station, TX).

For each combination of a preprocessing filter and match score algorithm, the percentage of true positives and false positives was computed. The percent correctly matched was calculated using receiver-operator-curve (ROC) analysis. In addition, an effect size was calculated (average match score of true positives divided by the standard deviation for all match scores). The optimal combination of image processing filter and match score algorithm was determined from the pooled comparisons. For the cervical region, the optimal filter and algorithm combination was a Histogram Equalization filter (improves contrast when the pixel value distribution is similar across the image) followed by the Jaccard algorithm similarity coefficient (statistical measure of the similarity between sample sets). For the lumbar region, the optimal filter and match score algorithm was Adaptive Histogram Equalization filter (improves contrast when the pixel value distribution is not uniform across the image) followed by the Jaccard algorithm similarity coefficient. These combinations of filter and match score algorithm produced greater than 93% accuracy in correctly classifying ID pairs (98% for cervical, 93.61% for lumbar). Subsequent testing of the software was completed using these respective filters and match score algorithms. (See reference numbers 7-12 for detailed information on the selected filters and algorithms).

Once the optimal filters and algorithms were identified, the project moved forward with further coding revision of QMA® into the CADI software prototype and validation of the software for lateral views of the cervical and lumbar anatomical regions. In order to validate the CADI prototype, multiple test scenarios were executed using cervical and lumbar spine radiographs from the MMI-archived database and the second National Health and Nutrition Examination Survey, NHANES II, which is a nation-wide sample of 27,801 people (32). Over 54,000 radiograph comparisons were made during development and testing of the method.

Results

Statement of Results:

Cases were randomly selected for each test array based on age and sex, using only cases that had two neutral-lateral radiographs of the cervical spine taken at least two years apart. Multiple age and sex specific arrays containing 5-30 images and at least one ID Pair were assembled. Age and sex specific test arrays were also analyzed for combined C3-C5 elements and combined L1-L5 elements. In summary, the cervical vertebrae results ranged from 95-100% of the ID pairs correctly matched. The lumbar results ranged from 92-99% of the ID pairs correctly matched (Tables 1-2). When CADI chose the correct match, the calculated match score was approximately 15% higher than the match scores of the other radiographs included within the array.

Six additional validation tests were conducted. In Test 1, age and sex specific arrays were created using radiographs compiled from two separate clinical studies in order to analyze match scores separately by sex, age, and then sex and age combined. Within each age and sex specific group the influence of individual vertebral level on the correct classification of radiographs was also tested. In total, individual cervical vertebrae were correctly classified in 98.44% of males and 98.86% of females. Individual lumbar vertebrae were correctly classified in 94.08% of males, and 93.21% of females.

In Test 2, the influence of array size on correct classification was investigated using the male, 40-44 years, C3 level Test Array from Test 1. Test 2 included five ID pairs and a varying number of radiographs from different individuals (5-30 radiographs in increments of 5). All radiographs (100%) were correctly classified in this test regardless of the array size.

Table 1. The influence of sex, cervical vertebra level or age and sex on CADI classification of correct matches

Age range	Sex	Cervical Vertebral level	# of vertebral level-specific arrays	# of ID pairs	% correctly classified
Overall					
All age-ranges combined	Male and Female combined	C3, C4, C5 combined	83	23 to 31	98.69
Sex-specific					
All age-ranges combined	Male	C3, C4, C5 combined	48	14 to 18	98.44
All age-ranges combined	Female	C3, C4, C5 combined	35	9 to 13	98.86
Vertebral level-specific					
All age-ranges combined	Male and Female combined	C3	31	31	98.83
All age-ranges combined	Male and Female combined	C4	29	29	99.37
All age-ranges combined	Male and Female combined	C5	23	23	98.02
Age- and sex-specific					
40-44 years	Male	C3, C4, C5 combined	11	3 to 5	99.17
45-49 years	Male	C3, C4, C5 combined	9	3	100
50-54 years	Male	C3, C4, C5 combined	9	3	100
55-59 years	Male	C3, C4, C5 combined	9	3	94.95
60-64 years	Male	C3, C4, C5 combined	8	2 to 3	100
65-69 years	Male	C3, C4 combined	2	1	100
40-44 years	Female	C3, C4, C5 combined	7	1 to 3	98.70
45-49 years	Female	C3, C4, C5 combined	9	3	100
50-54 years	Female	C3, C4, C5 combined	6	2	100
55-59 years	Female	C3, C4, C5 combined	9	3	97.98
60-64 years	Female	C3, C4 combined	2	1	100
65-69 years	Female	C3, C4 combined	2	1	100

The importance of non-age specific test arrays on correct classification was determined by Test 3. Two radiographs from different male individuals were randomly selected from each of the six age groups. The 12 radiographs formed a base array that spanned the entire age range from 40-69 years. One ID pair from each age group was added to the base array independently, forming six final test arrays. All radiographs (100%) were correctly classified in Test 3.

Test 4 examined the repeatability and reliability of the tracking process using QMA® and the masking performed by the analyst. Radiographs for the male, 40-44 years, C3 level Test Array from Test 1 were preprocessed (stabilization and masking) and re-tested on two separate occasions. All radiographs (100%) were correctly classified in both events of Test 4.

Table 2. The influence of sex, lumbar vertebra level or age and sex on CADI classification of correct matches

Age range	Sex	Lumbar Vertebral level	# of vertebral level-specific arrays	# of ID pairs	% correctly classified
Overall					
All age-ranges combined	Male and Female combined	L1, L2, L3, L4, L5 combined	192	46	93.61
Sex-specific					
All age-ranges combined	Male	L1, L2, L3, L4, L5 combined	109	27	94.08
All age-ranges combined	Female	L1, L2, L3, L4, L5 combined	83	19	93.21
Vertebral level-specific					
All age-ranges combined	Male and Female combined	L1	37	37	93.61
All age-ranges combined	Male and Female combined	L2	45	45	93.94
All age-ranges combined	Male and Female combined	L3	45	45	92.93
All age-ranges combined	Male and Female combined	L4	45	45	94.14
All age-ranges combined	Male and Female combined	L5	20	20	95.45
Age- and sex-specific					
40-44 years	Male	L1, L2, L3, L4, L5 combined	9	3	98.99
45-49 years	Male	L1, L2, L3, L4, L5 combined	15	5	95.15
50-54 years	Male	L1, L2, L3, L4, L5 combined	24	6	95.08
55-59 years	Male	L1, L2, L3, L4, L5 combined	30	6	93.64
60-64 years	Male	L1, L2, L3, L4, L5 combined	25	5	93.09
65-69 years	Male	L1, L2, L3, L4, L5 combined	6	2	95.45
40-44 years	Female	L1, L2, L3, L4, L5 combined	8	2	92.05
45-49 years	Female	L1, L2, L3, L4, L5 combined	8	2	96.59
50-54 years	Female	L1, L2, L3, L4, L5 combined	10	2	96.36
55-59 years	Female	L1, L2, L3, L4, L5 combined	12	3	93.94
60-64 years	Female	L1, L2, L3, L4, L5 combined	20	5	93.18
65-69 years	Female	L1, L2, L3, L4, L5 combined	25	5	92.73

Test 5 found that varying the pool of comparison images did not affect correct classification of radiographs. All of the radiographs (100%) were correctly classified using two test arrays with different individual radiographs compared to the same ID pair.

Test 6 determined whether multiple correct matches could be identified in a single test array. An age and sex specific test array was created with five ID pairs and five incorrect match radiographs. Thus, each of the five ID pairs was tested against nine incorrect match radiographs. All five of the ID pairs (100%) were correctly matched.

In summary, the CADI cervical vertebrae results ranged from 95-100% of the ID pairs correctly matched. The CADI lumbar results ranged from 92-99% of the ID pairs correctly matched. Following compilation of the CADI cervical and lumbar vertebrae results, a brief comparison of CADI accuracy with traditional anthropologic radiograph comparison was performed. Six forensic anthropologists encompassing a range of years of radiograph comparison experience assessed 27 test arrays for which CADI had reported the correct match for the cervical vertebrae bodies. The anthropologists were allowed to use all morphological features observed in the lateral radiographs of the cervical spine. The anthropologists' results ranged from 88.88% to 100% of the ID pairs correctly identified, slightly lower than the results generated by CADI for the bodies only.

Forensic Expert Panel Web Conference:

A description of the CADI method and the results of the validation testing were disseminated to a panel of four forensic experts through a Power Point presentation in June 2013. The panel was comprised of three forensic anthropologists (two with ME/C experience and one with military decedent recovery experience) and one practicing medical examiner whose sub-specialty is radiology. A set of discussion questions (Appendix A) were provided to the panel for their feedback on the method in terms of the level of scientific acceptability and the efficacy of the CADI approach for routine use in identification. The panel then joined the principal investigator, co-investigators, and the project postdoctoral fellow in a web conference version of a round table discussion.

The panel indicated that they rarely are called to the witness stand to testify on the identification of the decedent. However, three of the four members had testified regarding the

positive identification of at least one case. The members of the panel who currently work in the ME/C reported that they primarily rely on fingerprints, dental comparison and radiograph comparison to identify decedents with a tentative name. DNA assessment is usually the last option for the participants due to financial and time constraints. One panel member reported that when the radiographs are available, she prefers to use chest radiographs with a focus on vertebral features. Two members were relatively confident in the use of the frontal sinus and/or dental radiographs.

The panel requested clarification on stabilization of images, match scores, thresholds for a match, sample size, the limitations of the method, and the practical application of the software. These issues were further explained by the HCIFS and MMI researchers and the panel members regarded the explanations to be satisfactory. At least two of the members are of the opinion that quantitative results for anthropologic methods of identification are crucial. One member stated that “the concept is exciting and it is apparent that the researchers have put a lot of thought into the development process”. The panel listed the following as strengths of the method:

- Statistical probabilities can be assigned to an antemortem/postmortem radiograph image comparison.
- CADI is able to remove size and orientation as factors in the comparison.
- The CADI developers are aware of the questions that forensic scientists want answered in the quantification of identification methods.

The following were noted as potential weaknesses of the method:

- CADI cannot currently determine a non-match because a statistical threshold for a correct match has not been developed.

- The actual cost and turnaround time are not yet identified. If the method is not cost-efficient or the turnaround time is too long, it will not be an improvement over the current methods of choice.

Conclusions

Discussion of Findings:

The results of the validation testing show that CADI can choose the ID pair as the correct match 95-100% of the time when assessing radiographs of the lateral cervical vertebrae. CADI can choose the correct match 92-99% of the time when assessing the relatively uniform shapes of the lateral lumbar vertebrae bodies. Use of the software program greatly reduces analyst subjectivity and the CADI prototype is equipped with an analyst-friendly interface. Results generated by CADI are quantitative and replicable. The preliminary findings are quite promising but further development and testing of the method, including validation of the software using postmortem images is necessary.

In casework applications, the technology developed through this project might be used to augment an expert opinion. The CADI technology spatially registers specific anatomical features in two radiographs. After that is accomplished, the expert can flip back-and-forth between two radiographs with the specific anatomic feature held in a stable position on the display. That process facilitates interpretation of the similarities and differences between two radiographs. In addition, the software would objectively determine if the presumed antemortem radiograph can be picked out of an array of radiographs from known incorrect matches. Just as the end-user would have to judge the reliability of the expert opinion, the end-user would have to judge whether the quantitative CADI results increase or decrease confidence in the analyst's opinion.

There are substantial challenges in statistical interpretation of the CADI method and results that have been recognized but not yet solved. One important challenge is that the software calculates a match score for all comparisons, correct and incorrect matches, in a test array. Two pathways have been considered to address this challenge (verification or identification). One verification option is to calculate a match score for a large number of correct and incorrectly matched radiographs and identify the magnitude of match score that is optimally sensitive and specific (33). Match scores above the threshold would support a certain probability of a correct match. With that option, the results of the validation tests should only be used if the type of radiograph (e.g., lateral cervical, AP chest, AP pelvis, hip, etc.) and quality of the radiograph from the actual case is equivalent to the type and quality of radiographs in the verification. Probability would be based on the radiographs used in the validation, and individualized probability statistics would not be generated for each antemortem/postmortem radiograph pair that is tested. In this verification scenario, the result of the test would be “verified” or “not verified”, with the definition of “verified “ requiring a full understanding of the validation experiment that was used to establish the threshold. The project investigators decided not to pursue this option because the magnitude of the match score depends on many factors, such as the relative size of the specific anatomic feature being tested relative to the size of the ROI, the number of edges that exist after binarization, etc.

Another verification solution to the challenge is to use normalized match scores. The highest match score is set to 100 and all others normalized to that. If CADI is successful, the correct match will have the highest match score, and all match scores for non-matching images will be substantially less. After normalization, it is desirable to have a large gap between the normalized score for the correct match (which should be close to 100), and all other match scores

(which should be much less than 100). The probability that a correct match has been found can be based on validation experiments to determine a threshold level of difference between normalized match scores. It might be stated, for example, that if the average match scores for known incorrect matches is $< MS_1$, then the probability that a correct match has been found is P_1 , based on running the experiment for several hundred arrays. Alternatively, it may be possible to state, for example, that if the next highest match score for known incorrect matches is $< MS_2$, then the probability that a correct match has been found is P_2 .

The sensitivity and specificity of CADI in this verification mode can be calculated using data from validation experiments similar to calculations used in developing a diagnostic test in medicine. For example, it may be possible to state that there is $< P_\alpha$ % chance that CADI concludes the antemortem radiograph is a match to the postmortem radiograph when in fact it is not and that there is $< P_\beta$ % chance that CADI concludes the antemortem radiograph is not a match to the postmortem radiograph when in fact it is. These probabilities are understood to be based on prior validation experiments. The target probabilities that must be achieved to conclude that CADI results can be trusted in actual cases and the target probabilities that will allow CADI to be accepted in a court of law are not currently known. A limitation of this approach is that the probabilities are directly relevant only to the specific imaging used in the validation tests. It may be necessary to have different thresholds for each type of radiograph that might be used, and for each unique anatomic feature. That would be determined by completing appropriate validation experiments.

An alternative approach is to use CADI for identification as described above, rather than for verification. In that scenario, statistics can be based on the probability of picking a radiograph from a collection of radiographs by chance. That approach is analogous to a conventional police

line-up. CADI, as currently validated, has been used to test one anatomic feature at a time (e.g., the 3rd cervical vertebral body). CADI can be performed on multiple anatomic features seen in a radiograph (e.g., the 3rd, 4th, 5th, and 6th vertebral bodies). That would be analogous to an expert studying multiple different anatomic features in the comparison radiographs. It is a challenge to use results from multiple testing of multiple anatomic features to improve confidence that a correct match has, or has not been, found. The simplest approach is to recognize that if an anatomic feature in a postmortem radiograph is compared to the same feature in a collection of 11 radiographs (one of which may be a correct match), the probability of picking, by chance, the correct match from the 11 radiographs is 1 in 11. If a different anatomic feature is then tested, using the same collection of radiographs, the probability of picking, by chance, the correct match from the 11 radiographs is again 1 in 11. The nominal probability of picking, by chance, the correct match in both tests is $1/11 * 1/11 = 1/121$. This process can be repeated for multiple features, with the probability becoming smaller with each feature analyzed. In addition, the number of known incorrectly matched radiographs can be increased. For example, if a collection of 50 radiographs is used and 5 features tested, and the CADI test picks the correct match in each test, then the nominal probability that the radiograph was selected by chance is:

$$1/50 * 1/50 * 1/50 * 1/50 * 1/50 = 1/312,500,000.$$

However, it can be argued that a correction must be added since repeated tests are being performed on the same set of radiographs. That issue could potentially be mitigated by using a unique collection of unmatched radiographs for each anatomic feature tested. It is clear that to be of practical and defensible value, a method for identifying a decedent using ante- and postmortem radiographs must return a validated probability that the two radiographs are unique

compared to a population of known incorrect matches, or conversely, the probability that a closer match can be found in a population of known incorrect matches.

When used for verification or for identification, a computer-assisted radiographic method would ideally account for the prior probability that a forensics team could have found a matching antemortem radiograph within the community that they serve. Use of the prior probability can dramatically improve the reliability of a test, much as it does in a conventional police line-up, where there is a 1 in 5 chance that a perpetrator could be identified by chance alone, but the chance-probability of a perpetrator being found by police in the community where the crime occurred at about the time the crime occurred, and etc., is assumed to be very low. Based on the perceived (but largely untested) importance of the prior probability combined with the identification in a small line-up, the conventional police line-up is generally accepted

Implications for Policy and Practice:

The primary outcome measures of the project are the validated prototype of the forensic identification software developed from the revision of QMA® and construction of a model for future implementation in ME/C offices in which ME/C staff will be able to use an in-house computer workstation (node) to send radiograph data into a system monitored by trained analysts (Figure 2).

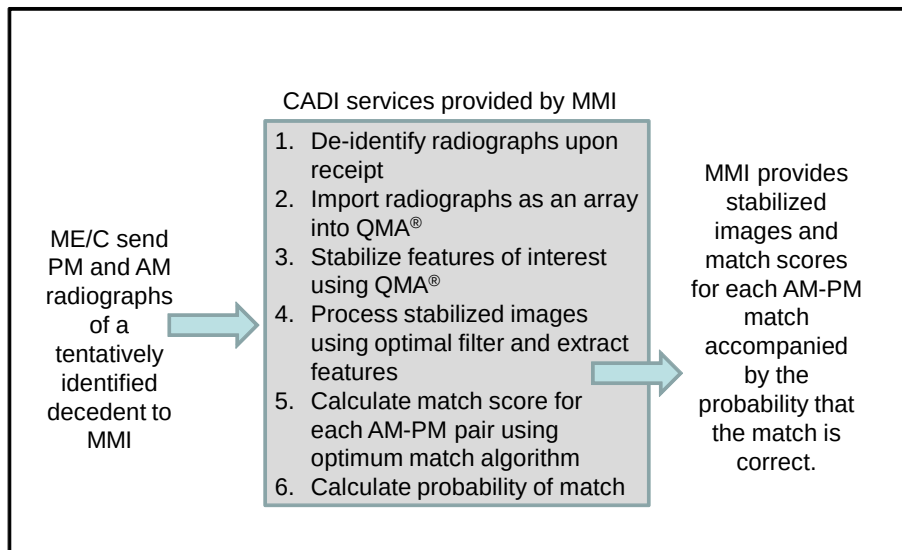


Figure 2. The Future CADI Model

The analysts would use CADI to compare the antemortem and postmortem radiographs provided by the ME/C and return a statistically supported match or non-match. For the ME/C staff this will be much like sending digital fingerprints to the Integrated Automated Fingerprint Identification System (IAFIS) for comparison with the forensic fingerprint database. However, the analyst receiving the images will use the forensic software to analyze all anatomic regions submitted and then generate the quantitative results with an error rate expressing the probability that the match supports identification.

The ME/C node model time frame for identification is an estimated two to three business days (with an option for a “rushed” case). The projected cost per case is \$150-\$200. This method is ultimately less expensive in cost and time in comparison to the HCIFS 2011 figures for the standard methods reported above. For each case identified through the proposed radiograph comparison system rather than the odontologist, HCIFS saves an estimated \$225-\$275. For each case that radiograph comparison precludes the need for a DNA profile comparison, the increased

cost is an estimated \$90-\$140 but the reduced waiting time for the anxious families is significant. In future iterations of the proposed model, it is possible that the CADI software can be revised to be sold to the ME/C and used in-house by trained ME/C staff.

The CADI method is efficient, timely, and is a promising solution to identification in the ME/C office when antemortem radiographs are available for a decedent with a tentative identity. The CADI prototype has the potential to become a cost-effective commercial product for use by ME/C offices.

Implications for Further Research:

Further research recommended and anticipated is a continuation of the interdisciplinary collaboration among the forensic anthropologists, biomedical engineers, and software engineers that developed the CADI prototype. The primary objective would be to further develop CADI into a practical and accessible commercial product for use in the identification of fleshed decedents.

In order to use CADI as a secure, quantitative method for identification, additional statistical research should be conducted as described under the Discussion section. The Joiner case described in the Literature Review above supports the view that “the use of multiple points of comparison increases the degree of certainty” (22). In this regard, CADI has the ability to test multiple skeletal elements to provide increased statistical support for the results of the comparison.

Testing of CADI using actual ME/C case work and additional anatomic regions of interest including the pelvis, hands, chest, and frontal sinuses are vital to statistical confidence in the method. A pilot project to test the usefulness of a computer “node” installed at participating

ME/C offices to provide ME/C access to trained CADI analysts for radiograph comparison results is proposed. The node concept and its potential for national implementation will be first evaluated on medicolegal casework at HCIFS. Data regarding accuracy and ease of use will be collected for each CADI node use. The results of the comparisons will not be used for official identification of remains until the method has been further validated using postmortem images.

A cost/benefit analysis will also be performed based on the actual costs of submitting CADI to external trained analysts. The costs of developing the software into a stand-alone program that could be purchased for internal ME/C use will be explored. With positive results, a plan for installation and testing of nodes at other large ME/C offices will be developed and implemented.

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Dissemination of Research Findings

Publications

Derrick SM, Raxter MH, Hipp JA, Goel P, Chan EF, Akella NS, Love JC, Wiersema JM. In press (November 2014). Development of a computer-assisted forensic radiographic identification method using the lateral cervical and lumbar spine. *Journal of Forensic Sciences*.

Raxter MH, Derrick SM, Hipp JA, Goel P, Akella NS, Love JC, Wiersema JM. In prep. Technical note: Quantitative analysis in skeletal radiographic comparison for identification. Target: *Journal of Forensic Sciences*.

Podium Presentations

Derrick SM, Raxter MH, Hipp JA, Love JC, Wiersema JM, Goel P, Sanchez LA, Akella NS. Testing a New Computer-Assisted Forensic Identification Method Developed through Interdisciplinary Collaboration. 2013; American Academy of Forensic Sciences 65th Mtg. Washington DC.

Derrick SM, Hipp JA, Love JC, Wiersema JM, Shi C, Tan Z, Sanchez LA, Akella NS. Ongoing Development of the Novel Computer-Assisted Radiograph Identification Method. 2012; American Academy of Forensic Sciences 64th Mtg. Atlanta, Georgia.

Derrick SM, Hipp JA, Love JC, Wiersema JM, Sanchez LA, Akella NS. New Method of Identification Based on Computer-Assisted Radiograph Comparison. 2011; American Academy of Forensic Sciences 63rd Mtg. Chicago, Illinois.

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Appendix A

Computer-Assisted Decedent Identification Radiographic Comparison Method Questions

1. What is your office's primary method of identification for decedents received with a tentative name?
2. What is your office's primary method of identification when the decedent is completely unknown and is moderately decomposed or skeletal?
3. Do you utilize radiograph comparison for ID purposes? If so, what is your primary modality (film, digital)?
4. Are you trained to use CT scans for image comparison?
5. What elements and features do you commonly examine when using radiographic comparison for identification?
6. Have you ever testified in court on decedent identification? If so, is it a rare occurrence or routine?
7. Do you think computer-assisted quantitative results for anthropologic methods of identification would be useful in court testimony?
8. Do you feel you have a general understanding of how CADI works from viewing the presentation?
9. What, if anything, was unclear to you about how CADI works?
10. What is your overall impression of the utility of CADI in aiding identification?
11. What do you think are the strengths of CADI?
12. What do you think are the weaknesses of CADI?
13. With further development and validation of the method, would you use CADI in the "node" to MMI (or another lab) configuration?
14. Would you use CADI if the cost per decedent is \$150-\$200?
15. If you do not feel you would use CADI, is cost the major issue or something else? If something else, what is the major issue?