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Accuracy of Bite Mark Overlays: A Comparison of Five Common Methods to Produce Exemplars from a Suspect's Dentition*

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ABSTRACT: Physical comparison of a suspect's teeth to a bite mark injury using hollow volume comparison overlays is a common forensic odontology technique. Several methods are used to record characteristics of the size, shape and position of the teeth and to generate overlays. These include computer-based, radiographic, xerographic and hand-traced methods. Five common overlay production methods were compared using digital images of dental study casts as a reference standard. Area of the biting edges of the anterior teeth and relative rotation of each anterior tooth were measured and compared. The computer-based production method was determined to be the most accurate of those studied. It produced accurate representations of the biting edges of the teeth in an objective manner. The radiographic method was determined to be more accurate than the xerographic method with respect to tooth area measurement. The opposite is true with respect to tooth rotation. Hand-traced methods, from either wax impressions of teeth or directly from study casts, were determined to be inaccurate and subjective. It is recommended that forensic odontologists discontinue the use of hand-traced overlays in bite mark comparison cases.

KEYWORDS: forensic science, forensic odontology, forensic dentistry, bite marks, bite mark techniques, overlays

Bite marks on human skin and other substrates may capture detail of dental characteristics present in a biter's teeth. Forensic odontologists analyze the comparative similarities and correlation between known teeth and unknown marks left on objects (1). One aspect of this comparison focuses on the three-dimensional features of the biting surfaces of the suspect's teeth. Two studies conclude these features are unique among humans (2,3). Neither study examines the resultant transference of the hypothesized individual characteristics to skin or similar media. Two recent commentaries reserve this uniqueness determination until further relevant population analysis research is completed (4,5). Questions of accuracy and inter-examiner error of the bite mark comparison process have been tested in one controlled study (1). The results were not favorable when experts compared teeth to two-dimensional images of experimental bite patterns.

Evidence analysis requires a comparison of the unknown mark found on skin or objects to known exemplars (Latin: *exemplare*, to show) of the suspect's teeth. These exemplars are typically plaster casts derived from dental impressions or a reproduction of the teeth obtained by other means. There are numerous methods available to the odontologist to reproduce two- or three-dimensional examples of the suspected dentition. These include styrofoam to record the shape and position of tooth surfaces (6), scanning electron microscopy (7), hand-traced outlines (8), wax impressions (9), xerographic images (10), videotapes (11), computer imaging (12) and computerized axial tomography (13). This reflects the current freedom allowed by the discipline to permit the expert to use a "personal" preference for this phase of bite mark analysis. The Bite Mark Methodology Guidelines of the American Board of Forensic Odontology (14) and the scientific literature are non-determinative of the accuracy of these techniques.

The tooth exemplar, independent of which method is used to produce it, is called an "overlay" when biting surface data is transferred to a clear acetate. This product is physically compared to the injury on skin or a patterned mark. Hollow volume overlays record the perimeter of each tooth's biting surface and leave the inner aspect of the tooth image transparent.

The hollow volume overlay, containing representations of the teeth, is placed over an image of the bite pattern. Conclusions are reached by the odontologist about the relative concordance between the known exemplar and unknown pattern. An opinion as to the degree of correlation is currently determined by the experience, training, and skill of the examiner (15). A review of the forensic odontology literature reveals multiple techniques for overlay production (8–10). There is an absence of reliability testing or comparison of these methods to a known or reference standard.

A study was completed to measure the precision of bite mark overlay production methods. The three objectives of the study were: a) comparison of five overlay methods commonly used in bite mark analyses, b) computer- and statistical-based determination of the relative accuracy of these methods, and c) development of recommendations for improved standards for forensic odontology. Two important characteristics were evaluated: the area of each front tooth's biting surface and the relative rotation of each tooth on it's long axis.

Material and Methods

Thirty sets of upper and lower dental study casts were randomly selected from a Caucasian population pool ($n = 30$). Overlays were produced from the biting surfaces of the six upper and six lower anterior teeth using five production methods: a) computer-based method, b) hand-traced from stone casts, c) hand-traced from wax impressions, d) hand-traced from xerographic images, and e) the radiopaque impression method. Following is a description of each method.

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Computer-based Method—The technique described by Sweet and Parhar is used (16). Each pair of upper and lower study casts is positioned on the glass platen of a 300 dpi flatbed scanner (Hewlett-Packard ScanJet 4c, Hewlett-Packard Company, Palo Alto, CA) connected to a Power Macintosh 8500 computer with 96MB RAM, 120 MHz CPU, and 17-in. color monitor (Apple Computer Inc., Cupertino, CA). An ABFO No. 2 scale (Lightning Powder Co. Inc., Salem, OR) is positioned at the left-side of the study casts as a laterality marker and to ensure life-sized reproduction. The digital image is imported using the TWAIN-acquire feature of Adobe Photoshop v3.0.5 (Adobe Systems Incorporated, Mountain View, CA) as reported by Christensen and Alder (17). Brightness and Contrast are increased to improve the appearance of the biting surfaces. The file is saved to the hard drive.

A new layer named "Overlay" is produced in Photoshop. The biting surfaces of the six upper and six lower anterior teeth are selected without subjective input (Tolerance = 14). Using the Copy and Paste commands, the selection is transferred to the Overlay layer (see Fig. 1). Using the Stroke command, a 2-pixel wide line is produced around the selected area (hollow volume). The ABFO No. 2 scale is copied from the background layer and pasted into the Overlay layer. Right and left laterality markers are added using the text tool. The Overlay layer remains active and the background layer is inactive. The file is saved to the hard drive. The Overlay layer is exported to clear transparency film (see Fig. 2) inserted in an Apple LaserWriter 4/600PS high resolution printer (Apple Computer Inc., Cupertino, CA). The final dimensions of the life-sized image are verified by comparing the ABFO No. 2 scale in the printed image to the actual scale.

Hand-Traced from Dental Study Casts—A sheet of transparency film is positioned over the biting surfaces of each set of upper and lower study casts and stabilized with moderate finger pressure according to the technique described by Luntz and Luntz (9). Using a fine-tipped felt pen, the perimeter of the biting surface of each of the six upper and six lower front teeth is subjectively recorded by hand-tracing the outline while observing each tooth's size, shape, and anatomical position through the clear film (see Fig. 3). A laterality indicator (right-side) is added. The hollow volume overlay is assumed to be life-sized because it is generated from the actual study cast of the teeth.

Hand-Traced from Wax Impressions—The technique previously reported by Luntz and Luntz (9) is used. The upper and lower study casts are pressed into a single wafer of wax (Aluwax Dental Products Co., Grand Rapids, MI) to produce a shallow impression

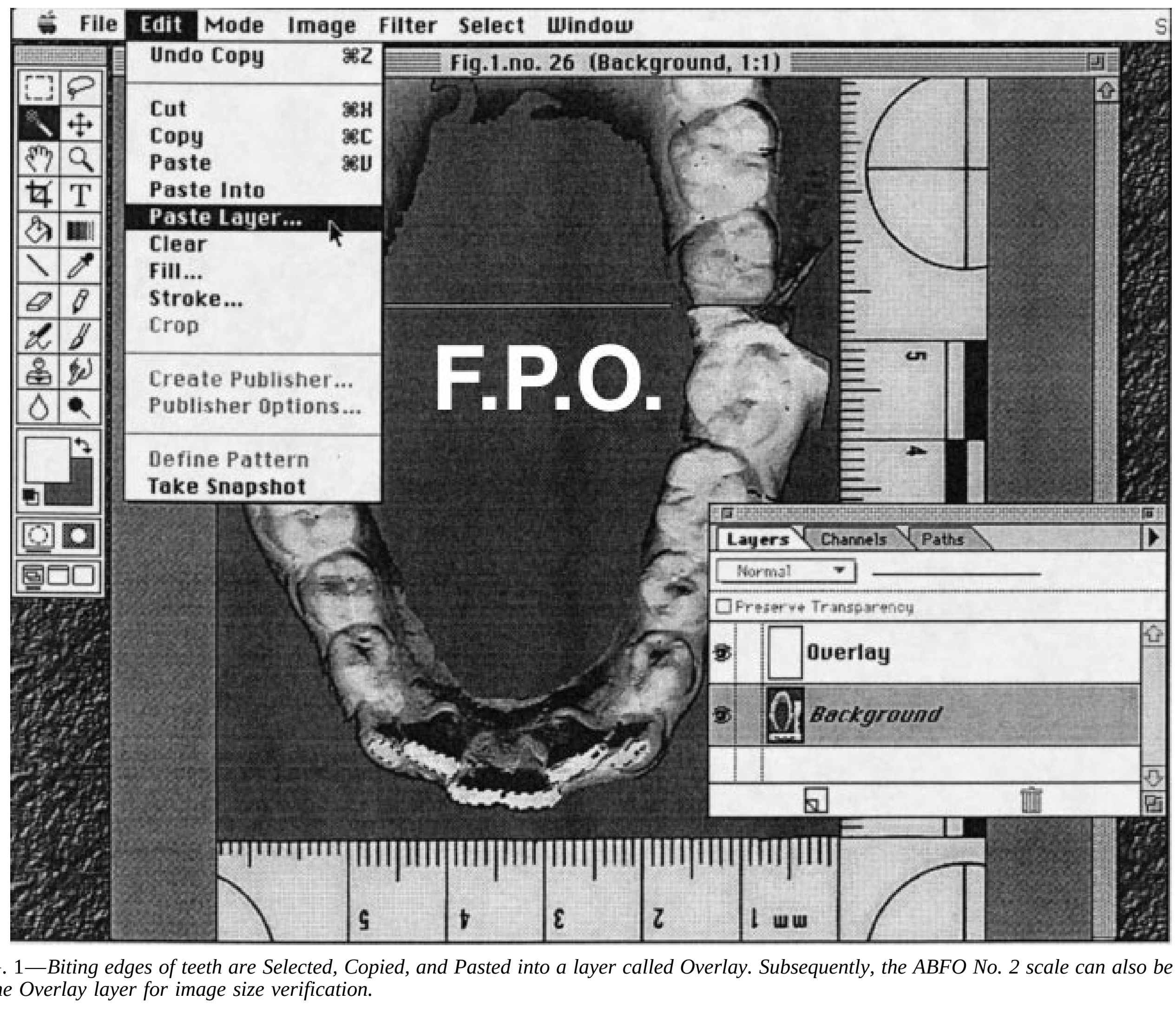

FIG. 1—*Biting edges of teeth are Selected, Copied, and Pasted into a layer called Overlay. Subsequently, the ABFO No. 2 scale can also be pasted into the Overlay layer for image size verification.*

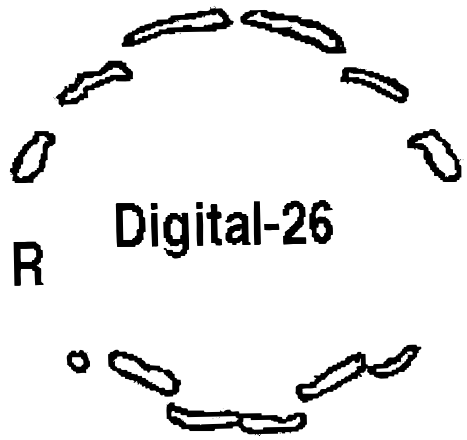

FIG. 2—*Computer-based hollow volume overlay produced using Adobe Photoshop from study cast no. 26. "R" indicates suspect's right-side.*

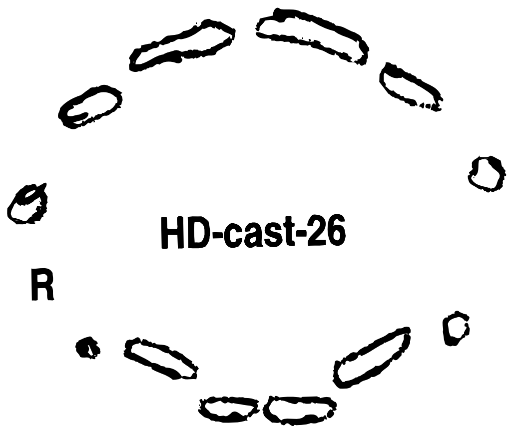

FIG. 3—*Hand-traced hollow volume overlay from study casts.*

of the biting surfaces of the six upper and six lower anterior teeth. A sheet of transparency film is stabilized over the wax. The perimeter of each of the depressions caused by the teeth of interest is hand-traced using a fine-tipped felt pen (see Fig. 4). A right-side indicator is added. The image on the overlay is assumed to be life-sized because it is generated from a wax impression of the study cast.

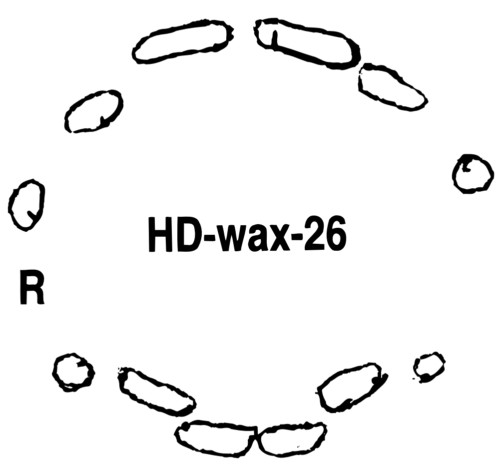

FIG. 4—*Hand-traced hollow volume overlay from wax impressions.*

Hand-Traced from Xerographic Images—Hollow volume overlays are produced using the technique described by Dailey (10). Each pair of upper and lower study casts is positioned on the glass platen of a photocopier (Model 3550, Toshiba Corporation, Tokyo, Japan) which has been calibrated to produce 100% images. An ABFO No. 2 scale is positioned as a left-side marker. A xerographic image is produced on white paper. The ABFO No. 2 scale in the image is compared to the actual scale to ensure life-sized reproduction.

The xerographic image is placed face-down on an illumination table. The biting surfaces of the six upper and six lower anterior teeth are subjectively recorded by hand-tracing the tranilluminated images using a fine-tipped felt pen. The image of the ABFO No. 2 scale is recorded as the left-side marker. The surface of the paper containing the traced images of the teeth (reverse of xerographic image) is placed face-down on the platen of the photocopier and a life-sized image is produced on clear transparency film (see Fig. 5).

Radiopaque Wax Impression Method—The upper and lower study casts are pressed into a single wafer of dental baseplate wax (Modern Materials Pink No. 3, Heraeus Kulzer, South Bend, IN) to produce a shallow impression of the biting surfaces of the anterior teeth (12). 600 mg of metal powder (Titan Amalgam, Kerr Corporation, Romulus, MI) are thoroughly mixed in 30 μL of isopropyl alcohol. Small quantities of the solution are sequentially added to the individual tooth impressions using a 5/0 gold sable hair brush. The solution is confined to the wax impression created by the incisal surfaces of the teeth of interest. The alcohol component is allowed to evaporate for approximately 5 min. The residual metal powder records each tooth's size, shape and anatomical position. A size 4 dental film (EO-41 6P, E speed, Eastman Kodak, Rochester, NY) is placed beneath the wax wafer. A radiographic image is produced on the film through the wax using the following exposure parameters: 70 kVp, 15 mA, 0.20 s, 45 cm focal distance. The radiographic image is scanned into Adobe Photoshop. Using the Inverse command, the image is reversed to produce a clear background with black marks from the biting surfaces of the teeth (see Fig. 6).

Sampling

The following dental characteristics were analyzed: a) area (sq. mm) of the biting edge of six upper and six lower anterior teeth, and b) degrees of rotation of six upper and six lower anterior teeth in relation to a zero degrees reference line.

Area of Tooth Biting Surface—Area measurement was included to evaluate differences in the relative length and breadth of recorded individual teeth and the width of the outline produced by each overlay method. Overlays produced using the various techniques described above were digitized and imported into NIH Image v1.6.0 software (Wayne Rasband, National Institutes of Health, USA). The area covered by the hollow volumes of each of the twelve anterior teeth (six upper and six lower) was recorded in square millimeters (see Fig. 8).

Rotation—Tooth rotation from a reference line was measured. A baseline intersecting the distal contact point of the right and left canine teeth for the upper and lower dental arches is produced using NIH Image. A line perpendicular to the baseline which bisects the space between the upper and lower central incisors is

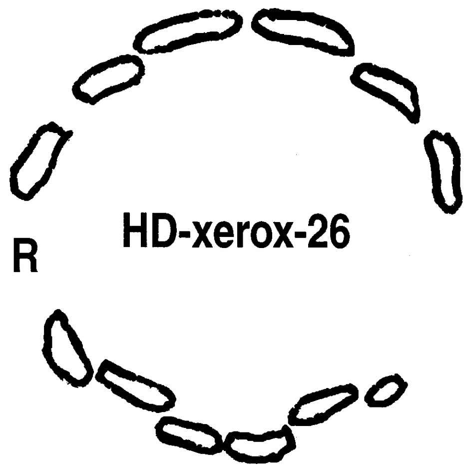

FIG. 5—*Hand-traced hollow volume overlay from xerographic images. Notice increase in size of representation of each tooth's biting edge.*

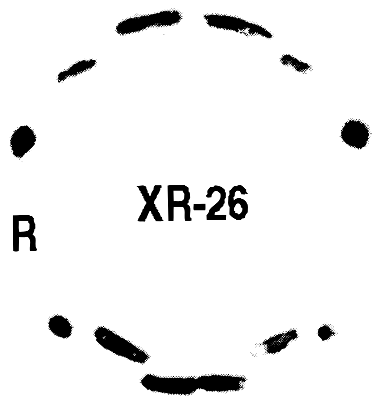

FIG. 6—*Overlay produced from radiopaque material in wax impression (not a hollow volume).*

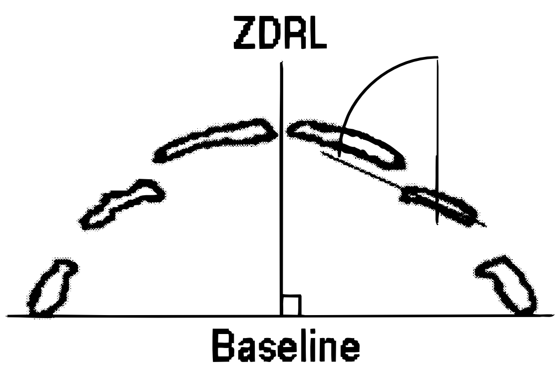

FIG. 7—*Relative rotation of each anterior tooth is measured in degrees from a line parallel to the Zero Degrees Reference Line to a line connecting the centroid and the mesial contact point.*

produced. This is the zero degrees reference line (ZDRL). The relative rotation of each of the incisor teeth (four upper and four lower) was recorded from the ZDRL to a line connecting the centroid and mesial contact points of each tooth (see Fig. 7).

Statistical Methods—Data was evaluated using the following statistical treatments: a) MANOVA, or multivariate analysis of variance, as an overall assessment of differences among the five methods (18), and b) Mahalanobis Distance to measure the relative

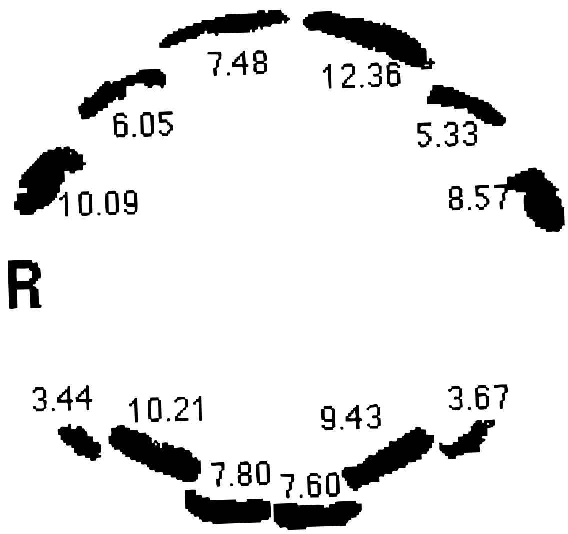

FIG. 8—*Area (square mm) of six upper and six lower teeth recorded using NIH Image software.*

TABLE 1—*MANOVA test statistic chi and p-values for area and rotation.*

	Area	Rotation
Test Statistic Λ	436.83	91.32
P-value	<0.0001	<0.0001

distance between a single multivariate observation and the center of the population that the observation comes from (19,20).

Results

The mean values obtained from measurements of tooth area for twelve anterior teeth and for the relative rotations of eight anterior teeth were calculated. Results of a MANOVA analysis are shown in Table 1, and the numerical results of calculation of the Mahalanobis Distance are shown in Table 2. The five overlay production methods were compared to the digitized study casts from which each overlay was produced. Table 3 shows the relative accuracy

TABLE 2—*Mahalanobis distances for each overlay method compared to computer-based method.*

	AREA		Rotation	
	Mahalanobis Distance	P-value	Mahalanobis Distance	P-value
Hand Drawn vs. Computer-based	138.53	<0.0001	16.64	<0.03
Wax vs. Computer-based	136.07	<0.0001	16.51	<0.04
Xerox vs. Computer-based	533.21	<0.0001	15.63	<0.05
Radiographic vs. Computer-based	17.08	0.15	28.37	<0.0004

TABLE 3—*Mahalanobis distances ranked in decreasing order of accuracy for area and rotation.*

Rank	Area	Rotation
1	computer-based method	computer-based method
2	radiopaque wax method	xerographic method
3	hand-traced from wax	hand-traced from wax
4	hand-traced from study casts	hand-traced from study casts
5	xerographic method	radiopaque wax method

with respect to area and rotation measurement of each method ranked in decreasing order.

Discussion

Data for area and rotation derived from the various overlay production techniques were analyzed using the MANOVA (18) statistical instrument. Results indicate the differences between the overlay techniques are statistically significant for area ($p < 0.0001$) and rotation ($p < 0.0001$) (see Table 1).

The Chi-square value indicates the range of data is greater for area than for rotation by a factor of approximately 5 (436.83 to 91.32). This indicates there is considerable variation in the determination of incisal edge area among the five overlay production methods. Area was measured using a computer-based method while tooth rotation was measured by geometrical means. Variation with respect to the rotational data sets between techniques appears to be much less than for area.

The Mahalanobis Distance (19,20) between each test method and the computer-based method was measured to reach conclusions about relative accuracy. Two results are derived for each overlay production method using this test. The first is the actual measure (unit value) of the distance from the test measurement to the mean of the gold standard data (see Table 2). The second ranks the various overlay production methods in terms of decreasing accuracy (increasing Mahalanobis Distance values). The accuracy of each method is determined by the amount of separation from the gold standard.

Area

Results determined for area measurements are ranked according to decreasing accuracy (see Table 3): a) radiographic technique (17.08), b) hand-drawn from wax exemplars (136.97), c) hand-drawn from dental casts (138.53), and d) xerographic technique (533.21). These results indicate serious problems exist for the commonly used xerographic overlay production technique. The basis for the extreme departure of this method from the standard is recognizable as instrumentation error. The xerographic image is produced by a static charge on a glass platen which attracts the photocopying ink (21). This produces a replicate image which is larger in area than the original, despite initial verification of linear accuracy using a scale on the glass platen.

Results using hand-drawn methods from wax exemplars and from dental casts (methods b and c) indicate that these overlays fail to accurately duplicate the dental characteristics of interest.

The radiographic technique is markedly more accurate than the others tested. This suggests that the interpretive demands, including subjectivity and bias, placed on the expert are reduced. This technique employs an objective method to place radiopaque material in the wax impression of teeth. Although subjective, this apparently records the shape of the incisal edges of the teeth more accurately than the other techniques.

Rotation

Results determined for tooth rotation are ranked according to decreasing accuracy (see Table 3): a) xerographic technique (15.63), b) hand-drawn from wax exemplars (16.51), hand-drawn from dental casts (16.64), and d) radiographic technique (28.37). Measurements for methods a, b, and c produced statistically insignificant differences.

The authors suggest that the interpretation of tooth width, centroid position, and ZDRL for these three techniques is subjective due to the geometrical basis of rotational measurements. These gross, non-unique dental characteristics are determined using techniques that are appreciably different in terms of area accuracy as long as the individual images are not distorted. Therefore, the inaccuracies identified previously do not affect the determination of rotational values. Rotational accuracy for the radiographic technique is not significantly different than the first three.

Five commonly used bite mark overlay production techniques were evaluated with respect to how accurately each reproduced the shape, size and rotation of the upper and lower anterior teeth. The computer-based method produced digital images of dental study casts which were found to be very accurate. This method was treated as the "gold standard" and the other methods were compared to it. The area of the biting edge and relative rotation of each upper and lower front tooth were recorded and compared. The radiographic overlay production method was determined to be the most accurate for tooth area followed by hand-traced and xerographic methods. With respect to tooth rotation, the computer-based method was determined to be the most accurate followed by xerographic, hand-traced and radiographic methods respectively.

Notwithstanding the limitations of each overlay production method identified in this study, the authors recommend that hand-traced methods which depend on subjective input by the odontologist be discontinued. Use of radiopaque media in wax dental impressions appears to be superior to other methods to determine the area of the biting edge. The use of a photocopier calibrated to produce 100% images appears to be superior to other methods to record tooth rotation. Clearly, computer-generated bite mark overlays provide the most reproducible and accurate exemplars.

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