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An Evaluation of the Mathematical Approach to Bitemark Analysis: Do Teeth Really Tell It All?

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Disciplines

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ABSTRACT

Bitemark analysis is one aspect of forensic science that has been contested since its appearance in the late nineteenth century. Its use is based on two main assumptions made by forensic dentists- that human dentition is indeed unique to each individual and that this uniqueness is able to be replicated in a bitemark. The procedures used to identify the varying characteristics of bitemarks in human skin and other materials cover such a range of analytical methods that is it not surprising to find experts reaching different conclusions. In addition, a majority of these methods lack a solid scientific background as support. The purposed method is a mathematical approach using angles and lengths between the anterior maxillary and mandible teeth to attempt to determine uniqueness of dentition. Fifty post-orthodontic dental casts from mostly young (15-43 years, mean= 17.74 years) individuals, formed the primary source for the evaluation of this method. While the results indicate that angles are good indicators of individuality among bitemarks, lengths do not provide such valuable evidence. In addition, 10 casts' lengths and angles were re-evaluated for a comparison to the original trial as evidence of the method's reproducibility. Only one comparison out of the 20 values proved to be statistically different, allowing the assumption that the method gives consistent results upon reproduction.

INTRODUCTION

In the forensic field, many variables can help identify individuals involved in a particular crime. From biological evidence such as DNA to physical evidence such as clothing material, forensics has developed many new techniques to ensure the identification of the correct perpetrator. Contrary to the growth and acceptance of these methods, the analysis of bite marks is one aspect of forensics that is still in dire need of a universally accepted and accurate identification method.

BITE MARK OVERVIEW

Definition

A bite mark is a dental impression left in a distortable surface. It can appear in anything, ranging from human skin to food and has the possibility to identify an individual. Often, a bite mark in skin and other materials consists of imprints from the anterior teeth. Their forward position in the mouth provides them the ability to bite surfaces more efficiently than molars and is probably the reason behind why the front teeth are used most often. This property is advantageous because the front teeth provide the best evidence due to unique shape and pattern of biting edge.[1] These tooth marks are usually rectangular, representing the incisors, or first fourth teeth, and triangular, representing the canines.[2] According to a compilation of various studies, at least four or five of these tooth injuries must be present to conclude a positive identification.[3] Fortunately, these front teeth are usually visible in many cases.

Bitemarks can occur for many different reasons. Conflicts between children can result in bite marks, though this is one instance that is usually not used in forensic cases. A more prominent and useful event is when a victim bites as a form of defense. These marks are usually found on the arms of the attacker and provide evidence of the attacker's presence at the crime scene. The most prevalent type of bitemark found and used in a forensic investigation and subsequent trial is found on the victim. The attacker usually bites the individual as a form of dominance or rage in a sexual act or form of control in a struggle. Women during these sexual acts are usually bitten on the breasts and legs, while men are bitten on their shoulders and arms.[4] Similar to the defense marks, these marks provide evidence that an individual was present at the crime scene, but also provide information of the malicious intent of that individual. These analyses

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[1] Thali MJ, Braun M, Markwalder TH, et al. Bite mark documentation and analysis: the forensic 3D/CAD supported photogrammetry approach. *Forensic Science International.* 2003: 135; 115-121.
[2] Sweet D, Pretty IA. A look at forensic dentistry – Part 2: Teeth as weapons of violence- identification of bitemark perpetrators. *British Dental Journal.* 2001; 190: 415-418.
[3] Strom F. Investigation of bite-marks. *J Dent Res.* 1963;42:312-316
[4] Sweet & Pretty

usually have a controversial, but significant impact in trials, and are used throughout the United States and world as evidence to identify suspects in criminal cases.

History

The idea of bitemark uniqueness is not a modern concept, but a rather old one. There has been evidence of the use of teeth as a form of identification for at least a millennium. In the mid 11th century, William the Conqueror used his dentition as a way to authenticate his documents. Instead of using a stamp in hot wax to seal his letters, he would bite into the wax to ensure the receiver that the document was indeed from him. Another example, recorded many years later, shows this same idea of using teeth as a type of signature. Debtors, sentenced to servitude in America, would sign agreements by biting the seal. The mark was believed to be authentic to the individual and therefore gave validity to the sentence given. This action is one speculation as to why they were called indentured servants.[5]

However, bite marks were not used as evidence in criminal cases until 1870, in the case of Ohio vs. Robinson. The court charged Ansil Robinson for murdering his mistress, using bite marks found on the victim's arm as evidence. Mr. Robinson was acquitted of the charges despite the support of bitemarks. Nevertheless, this case initiated the use of bite marks in human skin as a way to identify a criminal and over the next century, the use of bitemarks as evidence in trials began to flourish. Some of the first cases include Doyle vs. State in Texas, which used a bitemark in cheese as valuable evidence, and Illinois vs. Johnson, which used bitemarks to convict a criminal of rape.

[5] Rothwell BR. Bite Marks in Forensic Dentistry: A Review of Legal, Scientific Issues. JADA. 1995; 126: 223-232.

To date, one of the most prominent cases that used bitemarks for a conviction was the trial of the serial killer Ted Bundy. Over the years 1974 to 1979, Ted Bundy killed between 33 and100 women. His method of attack was to pose as a man with a broken leg that needed help with his boat or car. When he was able to convince a woman to help him, he would rape and kill them. However, the murder that led to his conviction was done in a sorority house at Florida State University. He raped and bit a young woman on both her nipple and her buttocks. In the courtroom, these bitemarks proved to be the major evidence that led to his conviction of her murder as well as countless others.

A forensic dentist, Dr. Richard Souvinor, was the expert witness that proved Bundy's connection with the young woman's murder. He began by explaining the significant anomalies of Ted Bundy's dentition such as chips, the size of his teeth, and sharpness of his bicuspids and lateral and central incisors. With this information, he went on to lay a transparency of Bundy's teeth over the bitemark left on the victim. The direct match of the two proved the connection between Bundy and the murder unquestionable. This evidence as well as biological evidence found at scenes of other crimes led to the incarceration and subsequent death of Ted Bundy in1989.[6]

Basis of Identification

The ability for courts to use bite marks rests on the scientific explanation of how and why teeth formation and arrangement in the mouth are different among individuals. The concept of the uniqueness of dentition comes from the notion that the emergence of teeth from the mandible and maxillary cavity and gums produces a distinctive

[6] Bergamo C. Biting Isn't Nice: What Ted Bundy Should Have Learned As A Child. NURS: 334: Forensic Science I. University of Pennsylvania. March 2004.

arrangement within the mouth.[7] After this eruption, the genetics and lifestyle of the individual further the dentition's individuality. According to forensic dentists, attritional wear, congenital malformations, missing, broken or chipped teeth, displaced or rotated teeth, diastemas, extent of shoveling of the maxillary incisors, presence and angulations of impacted teeth, restorations, caries, prosthodontic appliances, bone level, and dental anomalies are all important features that can appear in bite marks and increase the likelihood of a correct identification.[8] For example, if an individual is genetically predisposed to larger teeth, their teeth marks will have a unique size, while an individual inclined to grinding their teeth will have a characteristic dullness. The degree of either of these components is also an important part of the variability of tooth marks, with every individual varying on how big their teeth are or how much they grind their teeth. Additionally, the treatment of teeth is an important factor in uniqueness. If one is more prone to eating sweet food or chewing on harder foods, the dentition might be overwhelmed with filled, chipped or rounded teeth, while an individual with impeccable dental hygiene will have an almost perfect imprint. In effect, the more anomalies an individual has in their dentition, the more successful an accurate identification becomes and the easier it is to convince a jury of guilt or innocence.

In addition to the idea that dentition is unique, there is a second assumption made for bitemark analyses. This supposition centers on the principle that skin accurately portrays the dentition as it is in real life. This issue is two-part, in that, it relies on both the skin's ability to correctly portray and preserve the bite mark and on a bite's ability to

[7] Sweet & Pretty
[8] Delattre VF, Stimson PG. Self-Assessment of the Forensic Value of Dental Records. *J Forensic Sci.* 1999; 44: 906-909.

produce a replicate of the individual's dentition.[9] These two issues are directly related to the non-uniform properties of skin. Skin's varying layers, uneven surface and elasticity have a good probability of producing ill-defined tooth marks.[10] This idea goes hand in hand with the fact that individuals are bitten in different places on the body, which each have its own specific uniqueness that needs to be taken into account.[11] A bitemark on a leg with highly developed muscle will not produce the same imprint as a mark on the breast or other fatty tissue. The muscle is not as distortable and proves to be a harder surface than fatty tissue, which will move under the pressure of a bite. This difference in skin composition can lead to very different marks.

Skin is also prone to bruising and distortion with the applied pressure of the bite, making both the identification of the mark as originating from a tooth and the delineation between the tooth mark and the bruise a very difficult endeavor.[12] An additional characteristic of skin that proves an obstacle in analyzing a bite mark is its ability to heal itself. When a bitemark is not analyzed quickly enough in a living victim, it has the capacity to heal itself. If the victim is dead, rigor mortis deforms the mark. Due to these abilities, impressions, pictures, and other analyses of bitemarks need to be done as soon as possible after a crime has occurred.[13]

Aside from the imperfections of skin, the act of biting is a highly dynamic process. It involves the movement of two systems, the upper and lower teeth[14], known as

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[9] Thali, Braun & Markwalder
[10] Thali, Braun & Markwalder
[11] Al-Talabani N, Al-Moussawy ND, Baker FA, et al. Digital Analysis of Experimental Human Bitemarks: Application of Two New Methods. *J Forensic Sci*. 2006: 51; 1372-1375.
[12] Sweet D. Parhar M, Wood RE. Computer-Based Production of Bite Mark Comparison Overlays. *J Forensic Sci*. 1998; 43: 1050-1055.
[13] Sweet & Pretty
[14] Thali, Braun & Markwalder

the mandible and maxillary teeth.[15] This process can cause a scraping mark or uneven imprints due to changing pressure and the elasticity of the skin. In addition, the amount of force and angle at which it is applied can have a profound effect on the visibility and recognition of individual teeth within the mark. The larger the force the more pronounced the separate tooth marks will be in the skin, making the analysis somewhat easier. At the same time, if an angle other than 90° to the skin is taken, the teeth that are imprinted may be shifted toward the angle at which the force is applied. It can also distort the skin toward that side of the mouth and angle, making an impression and subsequent analysis very difficult.

Due to this problem of skin and bite mark variability, bite mark evidence is a lot more valuable in eliminating suspects than in identifying them.[16] This concept is based on the idea that if a bitemark shows a particular anomaly, such as a missing tooth, and the suspect has all of his or her teeth, then that individual can be omitted from questioning. Additionally, elimination can be used the other way around. An individual with a missing a tooth cannot be matched to a bite mark where the tooth is present. In this way, it is a lot easier to look at the key identifying factors found in both the individual's dentition and in the bite mark to eliminate suspects than it is to analyze the bitemark and its distortions to match it to one person.

The Court System

Although, there have been many cases, starting in the late 1800s that have used bitemarks as a major piece of evidence in a trial, the dentitions ability to correctly

[15] Bowers CM. Forensic Dental Evidence. San Deige: Elsevier, 2004: p.13.
[16] Sweet & Pretty

distinguish between the identity of individuals has never been scientifically proven. Surprisingly, this issue has never been a problem in the courtroom. Juries trust and rely on the inductive, experienced based testimonies of experts rather than the deductive, mathematical and scientific presentation of evidence.[17] In other words, people would rather trust a dentist that works with teeth and identifies bite marks for a living, than have confidence in mathematical facts concerning the ability to identify bitemarks.

One major problem with the acceptance of dentists' experience over a scientific format, is the presence of human bias in observing bite marks. In a case from Illinois, People vs. Milone, the prosecution's experts claimed that the defendant left the bite mark while four experts from the defendant's side claimed it could not possibly belong to Milone. Regardless of this blatant inconsistency with the method of bite mark identification, the testimonies of the experts of both sides were allowed.[18] Instead of calling for a re-evaluation of the methods used by each expert, the judge decided it was up to the jury to delineate between the evidence provided by both sides. The expert's opinions were said to have added a supportive element to each side's argument and should be taken into account when reaching a decision. After this decision, bite mark evidence was accepted routinely in several sites across the country.

As can be seen from this case, bitemark identification lacks a true and un-biased method to evaluate the evidence to arrive at an unquestionable conclusion. In routine suspect identification processes, there is usually a line-up of individuals either in person or photographs in a book, and the victim picks the criminal from the line. The accuser is not simply given one person or photograph of the suspect and asked if it is him or her.

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[17] Kieser JA, Bernal V, Waddell JN, et al. The Uniqueness of the Human Anterior Dentition: A Geometric Morphometric Analysis. *J Forensic Sci*. 2007; 52: 1-7.
[18] Rothwell BR

They are expected to be able to pick them out of a randomly selected group if individuals to validate that they truly know who the individual is. This is not the case in bitemark analysis. Instead of using a group of dentition casts or replications to compare to the bitemark, the dentist is only given that of the suspected criminal. This procedure in itself provides a bias.[19] In turn, the validity of the comparison and overall evaluation is compromised because the expert may feel inclined to find similarities that are not there.

On the other hand, the American Board of Forensic Odontologists does have a procedure outlined to collect and analyze bite marks for use as evidence in a trial. The process for the bite mark analysis is as follows:

1. Swab surface for DNA
2. Obtain photographic evidence
3. Make impressions according to American Dental Association guidelines
4. Obtain tissue samples

Swabbing the surface of a bitemark for DNA is usually the medical examiner's duty, but is up to the odontologist to ensure that it has been done. This collection should happen as soon as possible because DNA can degrade over time.[20] The photographic evidence must be taken with and without a scale to evaluate the bitemark on the surface as well as the exact size of its measurements. It should be taken up close and at an angle that provides the least distortion. If possible, impressions should be taken in accordance with the American Dental Association's specifications to match to any dental information the suspects may provide. Lastly, if the individual with the bitemark is deceased the bitemark tissue should be removed and preserved to allow for the possible necessity of a future analysis.

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[19] Rothwell BR

[20] Sweet D, Shutler GG. Analysis of Salivary DNA Evidence from a Bite Mark on a Body Submerged in Water. *J Forensic Sci.* 1999;44:1069-1072.

The ABFO also has guidelines concerning retrieval of dental information from the suspected biter. Dental records and any dental history should be obtained to allow for a better understanding of the individual's dentition. The odontologist should also take extraoral and intraoral photographs of the individual, as well as do an in person examination of both. The extraoral examination is useful to note any specific factors that may influence the biting pattern, such as deviations in opening or closing of the mouth, facial asymmetry, and any occlusal deformities. Facial hair should also be noted in case it does appear in the bitemark. The intraoral examination is beneficial for missing teeth and any abnormality in the size of the tongue. Saliva should be retrieved to have a DNA comparison to any biological material found at the crime scene and to compare to any saliva that may have been recovered from the bite mark. In addition, impressions should be taken as well as sample bite marks to allow for a comparison. The impression will allow for the possible formation of a cast to use as a reference when analyzing the bitemark.

Furthermore, descriptions of the bitemark are mandated by the ABFO in order to use a bite mark as evidence in court. The imprint must have identification data such as the case number and examiner. It must describe the location of the bitemark in reference to the skin surface, body part and tissue characteristics. It should also include the size, shape, color, type of injury (abrasion, convulsion, etc.), and any another unique information that can be obtained from the bite mark. Together, all this information provides a brief and concise description of the mark in simple terms for lawyers, judges, and juries to understand.

The overall acceptance and weight of the evidence provided is left to the discretion of the judge and jury. These two parties usually know very little about the science of the provided bite mark evidence and are only able to take it at face value. To complicate this lack of knowledge further, different experts use different methods, and each one can give a slightly different result. This problem is the reason behind the need for a standardized and scientific method that shows little bias and can be well-understood by the court. In the end, the decision makers of the court have the liberty to decide what is credible and what is unlikely, and the more agreement there is on bitemark analyses, the more likely they will be able to validate its effectiveness.[21]

METHODS

Various Methods in Use

Regardless of the doubt of bite mark identification methods present in courts and in the forensic field, forensic science still uses bite mark identification with its basis upon the idea that every individual's dentition is unique and that this uniqueness transfers to the skin when bitten.[22] This foundation is evaluated through countless methods, most of which are accepted in court because the ABFO does not mandate a specific method of analysis.[23] Some of the methods used are Styrofoam impressions, scanning electron microscopy, hand-traced outlines, wax impressions, xerographic images, computer imaging, and computerized axial topography. One study by Bowers and Sweet, selected five of the most popular methods to determine which one identified bite marks with the best accuracy. Out of the computer-overlays, radiopaque impressions, and hand-traced

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[21] ABFO Bitemark Methodology Guidelines. 21 April 2007. http://www.abfo.org/ 25 April 2007.
[22] Kieser, Bernal & Waddell
[23] Rothwell BR

representations from stone casts, wax impressions, and xerographic images, the computer-based method ranked highest for both representation of the area and rotation of the teeth in the bitemark.

The computer-based approach used the upper and lower casts for identification purposed. The casts were placed on a flatbed scanner with a scale alongside it. The upper six and lower six teeth were selected to use for area and rotation evaluation. The image then was downloaded into the software program NIH Image. This program recorded the area of each tooth in millimeters and the angle of rotation in degrees. It was compared to the measurements taken from the hand-traced and radiopaque methods, and was the method that reproduced the bitemark with the most accuracy.[24] As is expected, the computer-based method is the leading practice used in the field, and is continuously undergoing improvements in the overall quality of the picture and program functions to highlight important identifying features.

Method in Question

One method that has not been extensively studied is a mathematical analysis of bitemarks. In the article "A Method for Mathematically Documenting Bitemarks,' James McGivney and Robert Barsleyput forth the hypothesis that a bitemark could be broken down into lengths and angles through measuring the centroid of each tooth injury in a bite mark. He proposed this approach to be the needed mathematical component behind bitemark identification.[25]

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[24] Sweet D, Bowers M. Accuracy of Bite Mark Overlays: A Comparison of Five Common Methods to Produce Exemplars from a Suspect's Dentition. *J Forensic Sci.* 1998; 43: 362-367.
[25] McGuivney J, Barsley R. A Method for Mathematically Documenting Bitemarks. *J Forensic Sci.* 1999; 44: 185-187.

In this method, the centroid is calculated as the square root of the summed squared distances from each landmark in the configuration in question.[26] In other words, it is the center-most point of an object or shape taking into account all characteristics of its size and figure. The centroid is located through an imaging program, as points on a grid, giving its value in X and Y coordinates. The centroids are then connected to the centroid of the next tooth by lines to form lengths between individual teeth. Then starting at the endmost tooth, the angles between the teeth are calculated as well. These measurements yield important information about the bite. Large lengths can mean a missing tooth or gaps, while small lengths are indicative of overlapping or small teeth. A sudden change in angle means the tooth is misaligned in the mouth, or the dentition is curving in its uniform arch.

If this information is retrieved from both the suspects bite pattern and the bite mark itself, a comparison would prove to be extremely valuable in identification. It might be able to single-handedly revolutionize the way bitemarks are evaluated by introducing a scientific basis to the previous inductive presentation of bitemarks. The combination of these two components would increase the validity of bite mark analysis and identification to an unquestionable science.

Unfortunately, McGivney does not provide experimental data to show whether this is truly feasible. He provides a detailed description of how it could be done, but there lacks any data of an actual experiment being performed. For this reason, this paper focuses on this method and uses an experimental format to determine whether it is applicable to the forensic field.

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[26] Kieser, Bernal & Waddell

MATERIALS AND METHODS

For this experiment, 50 post-orthodontic dental casts (male=19) of mostly young adults (15-43 years, average 17.74 years) formed the primary source. These dental casts, made of plasticine, were obtained from the archives in the Museum of Anthropology at the University of Pennsylvania. Post-orthodontic casts were selected because they are more likely to provide less variation, making the analysis more convincing. In addition, the presence of at least eight teeth that would make an impression (4 maxillary and 4 mandible) was compulsory. This qualification was mandated due to the previous knowledge that at least four teeth on each arch must be present for a credible identification. The literature also commented on the individuality and prominence of the front six teeth on both the mandible and maxillary in bitemarks, so both were used for imprints. Other selective criteria included the minimum age of 15, because teeth are mature at that age, and casts that were in perfect condition, because unwanted chips or missing aspects due to inappropriate handling would alter the impression made.

The 50 chosen casts then were pressed individually into a 7x7x1cm piece of plasticine. This material was chosen because it has the elasticity of skin and can maintain the imprint indefinitely.[27] The pressure applied to the upper and lower jaw of each individual varied due to the human application of the force. This is advantageous because not all bitemarks show the same pressure.

The impressions were then scanned using an HP scanjet 4600 scanner. The photo was copied into NIH's Image J software program. In order to allow analysis of the different tooth marks, the picture had to be adjusted to an 8-bit photo and the threshold

[27] Bowers

was changed to see the imprints in black with the background white (Figure 1 & 2). This allowed for easier identification of the individual tooth marks.

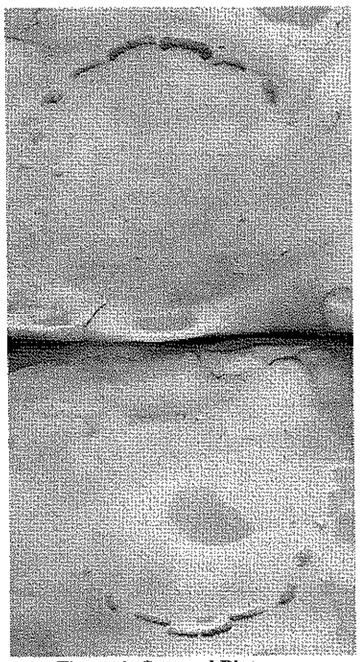


Figure 1: Scanned Picture

Figure 2: Mark with Threshold Alterations

In a counterclockwise patter, the individual tooth marks were outlined with the tracing tool and then analyzed to obtain their centroids. The coordinates given were used to draw a line between the centroid of the first tooth to the centroid of the next (Figure 3). In all cases, this connecting started with the upper right canine's centroid to the upper right lateral incisor's centroid and continued around the arch from there until reaching the left canine. This counterclockwise analysis was continued in evaluation of the bottom teeth, in that the starting tooth was the left canine and the ending tooth was the right canine. The lines were then analyzed for length and angle (Table 1).

Figure 3: Connection of Centroids

	Label	Angle	Length
1	94	136.22	0.33
2	94	150.02	0.3
3	94	-178.36	0.35
4	94	-145.78	0.3
5	94	-131.19	0.32

Table 1: NIH Image J Analysis Graph

This chart is a duplicate of the one formulated by the NIH Image J program. The numbers on the left side correlate to the lines formed between the centroids of the teeth in a counterclockwise direction. In other words, number 1 is equal to the line and angle between the right canine and right lateral incisor, while number 5 represents the values between the left lateral incisor and left canine. The label is the identification number given to the dental cast. The angle is measured in degrees and the length is measured in inches.

These measurements were then analyzed for differences between each other to see if the lengths and angles of bite marks are unique to each individual. The lines and angles of all 50 impressions for every upper right canine to every right lateral incisor were compared to each other and an average and standard deviation was calculated. This continued on for all the upper and lower teeth, producing a total of ten different analysis of lengths and angles between the teeth. The accuracy of the test itself was also evaluated by re-tracing and calculating the lengths and angles of 10 dental casts. The second trial was compared to the first trial using a paired T-test to establish whether the two were statistically different from each other.

RESULTS

Not all dental casts reproduced each individual tooth in its anterior dentition. This outcome was due to a missing tooth or the inability for the tooth to make an impression because of its relative size to the rest of the teeth. One example had both the maxillary lateral incisors missing and produced a unique bitemark (Figure 4 & 5). In actual trials, this type of anomaly would only help the identification process of an individual.

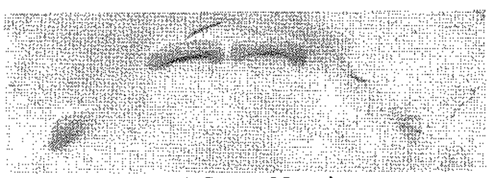


Figure 4: Scanned Imprint

Figure 5: Mark with Threshold Alterations

The actual number of dental casts that were able to produce lines and angles for each tooth are shown through the n value in Tables 2 and 3 respectively. It shows that there are more missing teeth and disproportional qualities between teeth of the upper jaw than those of the lower. More specifically, there seems to be a slight trend between upper canines and lateral incisors missing or being smaller than the rest of the dentition, in that the n value is less for these measurements (44 and 46 compared to 48 of the central teeth and 50 of the lower teeth). In this population of casts inspected, 11 individuals provided evidence of upper teeth that did not scan, meaning that one of the teeth was not able to make a mark due to the larger quality of the teeth around it or missing teeth. Only, two individuals showed evidence of bottom teeth that could not be scanned. This data provides evidence that the maxillary teeth have more anomalies than the bottom teeth, and may be more indicative of a certain individual than the teeth of the mandible.

Table 2: Lines (measurements in inches)

	Between*	N	Average (inches)	Standard Deviation	Minimum	Maximum
Maxillary	RC to RLI	44	0.32	0.034	0.25	0.39
	RLI to RCI	46	0.33	0.064	0.25	0.69
	RCI to LCI	48	0.34	0.033	0.27	0.41
	LCI to LLI	46	0.31	0.064	0.22	0.66
	LLI to LC	46	0.32	0.073	0.22	0.76
Mandible	LC to LLI	49	0.24	0.031	0.18	0.33
	LLI to LCI	50	0.22	0.027	0.16	0.27
	LCI to RCI	50	0.21	0.025	0.15	0.26
	RCI to LCI	50	0.22	0.024	0.17	0.29
	RLI to RC	49	0.24	0.031	0.18	0.32

***Key**

Right Canine: RC
Right Lateral Incisor: RLI
Right Central Incisor: RCI

Left Canine: RC
Left Lateral Incisor: LLI
Left Central Incisor: LCI

In addition, each bitemark obtained was analyzed and the average, standard deviation, and range for each line and angle were calculated. The lengths between each individual tooth shows evidence that the upper teeth are larger in comparison to the lower teeth due to larger lengths between the centroids of each tooth. Similarly, the standard deviation is also larger for the maxillary teeth. A surprising result is the similarity between lengths of all the teeth for the upper as well as the lower. The maxillary teeth have an average between 0.31 to 0.34 inch, and the mandible teeth have an average between 0.21 and 0.24 inch. Both only had a 0.03-inch range. Regardless of these similarities, the minimum and maximum values of each group as compared to the overall standard deviation shows the wide range of possibilities for each length. For this population, the upper tooth marks lengths ranged over 0.22 to 0.76 inch with an average of 0.32 inch, while the lower tooth marks ranged over 0.15 to 0.33 inch with an average of 0.22 inch. This statistic shows that the lengths may provide some individual character to the dentition but do not hold significant individuality. They do cover a range of possibilities, but the range is small.

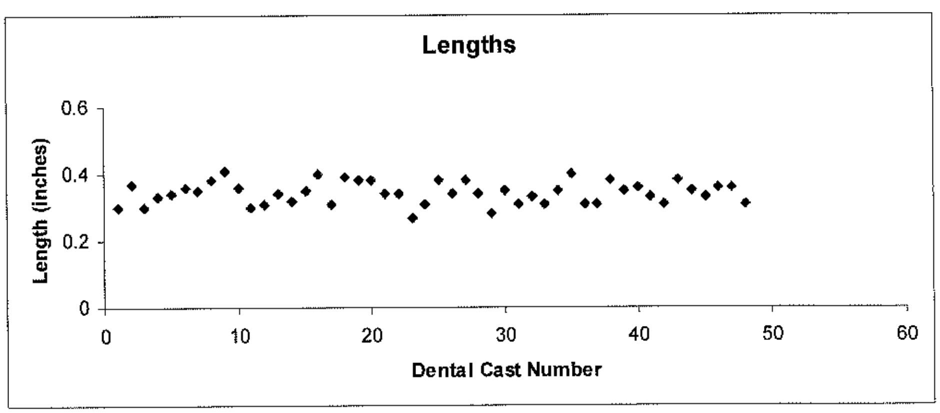
In the following table, the angles between neighboring teeth are demonstrated in the same format as the lengths.

Table 3: Angles (measurements in °)

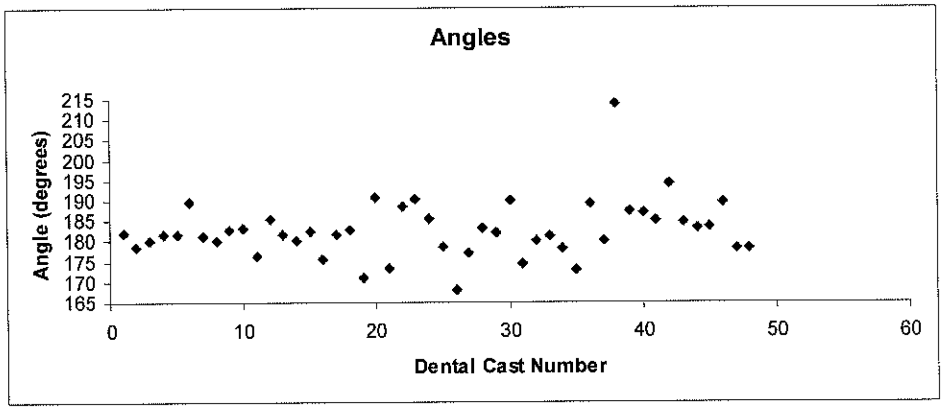
	Between*	N	Average (°)	Standard Deviation	Minimum	Maximum
Maxillary	RC to RLI	44	136.09	7.31	122.62	151.39
	RLI to RCI	46	156.81	9.21	141.84	180.00
	RCI to LCI	48	182.64	7.11	168.02	213.69
	LCI to LLI	46	208.33	9.62	180.00	237.09
	LLI to LC	46	228.39	8.34	212.62	228.39
Mandible	LC to LLI	49	-28.45	10.50	-50.19	-4.97
	LLI to LCI	50	-15.864	9.01	-33.69	10.78
	LCI to RCI	50	3.54	10.19	-21.80	30.26
	RCI to LCI	50	22.24	12.12	0	68.20
	RLI to RC	49	34.94	17.27	-29.05	72.26

In this table, the arch-like quality of the teeth is represented in the maxillary by the steady increase in angle, and in the mandible by the decrease and then increase in the angle. The maxillary does not provide negative angles because the values past 180° were given positive values to aid in the calculation of averages and standard deviations. For example, two numbers in the same length category would be 178.23° and then -177.36°, which when averaged, did not give a number that truly represented the mean between the two angles. Therefore, the negative number, -177.36°, was convert to 182.64°. On the other hand, the bottom angles were able to be kept as they were calculated because the average of the angles was representative of the actual mean. For example, two possible numbers were -3.4° and 4.5°, and the average truly represented the mean of the numbers.

As for the statistical analysis of the angles, the standard deviation is relatively large compared to the overall range of each angle, meaning that the angles truly had a significant difference between each other. Opposite to lengths, the ranges and standard deviation of the angles were larger for the bottom teeth than for the top. This difference provides evidence that the bottom teeth are less uniform in their arrangement to each other than the top. Along the same line, the standard deviation for the angles covers more of the range of each tooth mark than the standard deviation for the lengths. This difference further indicates that the lengths from tooth to tooth in bite marks are not as unique to each individual as the angles. Mathematically this makes sense, because a length can be rotated 360° representing every possible angle, while an angle is more static and revealing of the actual orientation. The following two graphs represent the dispersal of values for the lengths and angles between the central incisors of the maxillary. The lengths are more concentrated between a 0.14-inch range, while the angles spread over a 45° range.



Graph 1: Length Dispersal



Graph 2: Angle Dispersal

In addition to showing an association with lengths and angles to the uniqueness of human dentition, the method also was tested for its ability to be replicated to continuously reproduce the same results. This task was completed by recreating the measurements of 10 analyses. The 10 casts were randomly selected and exposed to the same procedure for calculation of centroids and analysis of the angles and lengths between teeth. The second trial length and angle measurements were then compared to the first trial's calculation using a paired T-test (Tables 4 & 5). For every individual length and angle except for one (giving a strong evaluation of 19 out of 20), the comparison proved to be statistically insignificant, with p-values over the accepted significance indicator of 0.05. This result means that the second trial was not different from the first, proving the method's ability to reproduce the same results.

Table 4: Comparison of Lines

	Teeth	Line (inches) Averages		T-test values
		Trial 1	Trial 2	
Maxillary	RC to RLI	0.30	0.31	0.23
	RLI to RCI	0.31	0.31	0.42
	RCI to LCI	0.34	0.33	0.14
	LCI to LLI	0.30	0.31	0.02
	LLI to LCI	0.32	0.31	0.28

Mandible	LC to LLI	0.23	0.23	0.22
	LLI to LCI	0.19	0.21	0.06
	LCI to RCI	0.21	0.20	0.06
	RCI to LCI	0.22	0.22	0.44
	RLI to RC	0.23	0.23	0.39

Table 5: Comparison of Angles

	Teeth	Angle (°) Averages		T-test values
		Trial 1	Trial 2	
Maxillary	RC to RLI	137.51	136.83	0.04
	RLI to RCI	161.49	161.73	0.72
	RCI to LCI	183.89	183.83	0.34
	LCI to LLI	205.36	203.63	0.07
	LLI to LCI	230.04	231.79	0.13
Mandible	LC to LLI	-28.17	-27.85	0.80
	LLI to LCI	-17.61	-15.93	0.08
	LCI to RCI	-2.21	-1.89	0.57
	RCI to LCI	17.04	18.46	0.07
	RLI to RC	41.56	40.82	0.22

DISCUSSION

In total, the mathematical approach to bitemark analysis has proven that the angles between teeth are different on a person to person basis, while the lengths do not provide as substantial evidence. The larger standard deviation and ranges of the angles compared to the smaller standard deviation and ranges for the lengths support this conclusion. When a value has a large standard deviation, it means that the values of the group being analyzed have a wider spread, making the individual values more unique. Therefore, the angles are more indicative of an individual person, while the lengths may be able to provide some support, but are not as unique.

The result of this analysis of the mathematical approach to bitemark identification has the possibility to be very useful to forensic dentists and the forensic science field overall. It can add a scientific and mathematical analysis to their testimonies in addition to their already established experience-based knowledge on bitemarks. A scientific approach that is based on math will add an unbiased variable to bitemark identification, giving a more credible and less controversial result to every expert's analysis of teeth. The judges and juries will also be more convinced of identification because not only will their favored deductive representation be present, but there will also be a solid scientific basis to it.

Additionally, this method can be duplicated with accuracy, which adds to its overall credibility as an analytical technique. As seen in the reproduction of 10 of the 50 upper and lower bitemarks measurements, there was only one significantly different result between the two trials. This quality is important in forensic science because many individuals will have to use the method for many types of bitemarks, and the ability for each analysis to produce an accurate measurement is extremely important. More notably, the ability for another forensic dentist to arrive at an identical result proves the method's credibility and consequent ability to convince a jury of an identification.

Despite the mathematical analysis' ability to show the uniqueness and individuality of a bitemark, it cannot be the sole assessment of a bitemark. The visual evaluation needs to remain present to obtain the best conclusion of identity. A mathematical analysis gives numbers and can provide a good basis, but if the numbers are not given in context of the bitemark and its individual qualities, it will be lost in a courtroom.

For instance, one of the casts made a 0° angle between the lower central incisors. If simply given this information, one might be led to believe that the teeth are perfectly aligned. However, this particular cast had centroids of the two front teeth that were on the same X coordinate, but the actual teeth were angled in a parallel manner that might leave a significant imprint (Figure 6).

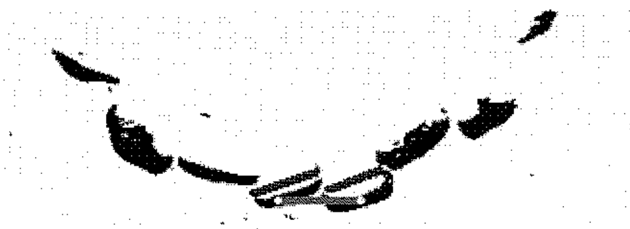


Figure 6: Reason for Visual Observance

In this case, the experience-based visual approach would probably be more valuable to the identity of the individual than knowing the angle between the two teeth. Nevertheless, having the mathematical background supply the information that both the individual's dentition and the bitemark in question are 0°, would provide a solid foundation behind the visual representation.

To further the credibility of the experience-based approach, a standardized evaluation method needs to be implemented. Presently, there are many different methods used, ranging from computer overlays to wax imprints, that visually match bitemarks to suspects. More research needs to be done to prove which method is the most accurate, so that it can become the standard application. With this improvement, the differences in outcomes and controversy over human bias should decline substantially and in turn, increase the credibility of the method's conclusions.

At the same time, more research needs to address the way skin responds to bitemarks. The knowledge of how this elastic and very dynamic material responds to particular bites will provide an immense insight into both the way the victim was bit and the details of the person's dentition that did the biting. It should also focus on the way bitemarks heal or settle overtime. Some bitemarks are not identified immediately after they occur, and can deteriorate or heal overtime. The knowledge of this process will increase the amount of time allowed before a bitemark is no longer able to be analyzed.

Ultimately, the presentation and acceptance of information in court is the crucial indicator of the evidence's value. The explanation of bitemark analyses in terminology that is understood by those less scientifically inclined can make a case significantly stronger in one direction or the other. In time, this combination of mathematical and experience-based methodology along with knowledge of dentition's uniqueness and skin's response to bitemarks will make bitemark identification extremely credible and a major force in the courtroom. With sufficient research, it may even one day rival that of the fingerprint.