

The Quantification of Displacement of the Anterior Teeth in the Human Dentition

Peggy Jean Van Scotter-Asbach
Marquette University

Recommended Citation

Van Scotter-Asbach, Peggy Jean, "The Quantification of Displacement of the Anterior Teeth in the Human Dentition" (2010).
Dissertations (2009 -). Paper 56.
http://epublications.marquette.edu/dissertations_mu/56

THE QUANTIFICATION OF DISPLACEMENT
OF THE ANTERIOR TEETH
IN THE HUMAN DENTITION

by

Peggy J. Van Scotter-Asbach, B.S., M.A.P.S.

A Dissertation submitted to the Faculty of the Graduate School,
Marquette University,
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy

Milwaukee, Wisconsin

August 2010

ABSTRACT
THE QUANTIFICATION OF DISPLACEMENT
OF THE ANTERIOR TEETH
IN THE HUMAN DENTITION

Peggy J. Van Scotter-Asbach, B.S., M.A.P.S.

Marquette University, 2010

The credibility of bite mark analysis as a forensic science is under fire in our legal system. The basis of opinions regarding the probability of a dental pattern observed in bite mark evidence matching a suspect's dentition has not been objectively substantiated. Though guidelines and standards are in place, bite mark analyses have failed to provide basic scientific methods in order to be deemed of evidentiary value. Forensic scientists need to take a step back and develop valid and reliable methodologies that provide a statistical approach for defining dental characteristics in the human dentition.

For this study, three computer-generated, mathematically derived curves were chosen to describe and quantify in a statistical manner the dental characteristic of displacement of eight anterior teeth in the human dentition. The Bezier, ellipse, and polynomial curves were digitally applied to scanned images from 75 dentitions comprising 150 wax exemplars of dental imprints of a male population, ages 18-44. Measurements of each tooth were made using Adobe Photoshop® software to provide maximum standardization and objectivity. Statistical tests established the best-fit-curve for determining displacement of the anterior teeth.

Of the three curves, the polynomial curve had the lowest average of variance and the lowest sum of the absolute value of displacement from the curve for the anterior teeth; thus, it was shown to be the best-fit-curve based on the statistical variance for measuring displacement of the anterior teeth. Allowing for tooth displacement to be a measurable dental characteristic that can be scientifically quantified, the polynomial curve provides a valid and reliable methodology for bite mark analysis in future population studies.

The polynomial curve may significantly enhance the judicial process associated with bite mark evidence by providing a scientific basis for objective interpretation of a unique dental characteristic based on an individual curve and the individuality of a bite pattern or imprint from a victim and/or suspect(s).

TABLE OF CONTENTS

LIST OF TABLES iii

LIST OF FIGURES iv

CHAPTERS:

I. INTRODUCTION 1

 A. Dental Forensic Science and the Law: The Partnership.....2

 1. Identification.....3

 2. Classification/Individualization.....7

 3. Association9

 4. Reconstruction10

 B. Statement of the Problem 11

II. DENTAL FORENSIC SCIENTIFIC ISSUES 14

 A. Evidence Collection 14

 B. Dental Testimony 18

 C. Issues of Individuality 22

 D. Current Literature Regarding Reliability and Validity.....25

 1. Scientific Method and Techniques25

 2. Credentials of Experts 26

 3. The Role of DNA 27

 4. Advances in Digital Imaging.....29

III. LEGAL ISSUES 33

 A. Modern Evidence Law Generally.....33

 B. Admissibility of Evidence 34

 1. Real Evidence 34

 2. Demonstrative Evidence..... 35

 3. Documentary Evidence 35

 4. Witness Testimony 36

 C. Constitutional Problems in Collection of Evidence 38

 1. Fifth Amendment.....38

 2. Fourth Amendment.....41

 D. Validation of Scientific Evidence: The Power of Expert Testimony48

 1. General Acceptance Test: The Frye Test51

 2. McCormick’s Relevancy Standard.....54

 3. Federal Rule 702.....57

 a. The Daubert Reliability Standard.....58

 b. The *Joiner* Case.....60

 c. *Kumho Tire*61

 4. The Seachange: Current Rule 70263

IV. THE STUDY.....71

 A. Research Question71

 B. Materials and Methods74

 1. Teeth in Question74

2. Mathematical Curves to Measure Displacement	75
a. Bezier Curve	77
b. Polynomial Curve.....	79
c. Ellipse Curve	79
3. Defining Displacement: Need for a Decision Tree	81
4. Creating Exemplars	82
5. Imaging the Exemplars.....	83
6. Utilizing the Wirtz Program: Generating the Three Curves.....	86
a. Bezier Curve.....	87
b. Polynomial Curve.....	89
c. Ellipse Curve	90
7. Measuring Displacement	91
C. Results	96
D. Data Summary	114
E. Discussion.....	115
1. The Challenges in This Research	115
a. Using the Appropriate Curve	115
b. Materials for Scanning	117
c. The Measuring Tool	118
d. The Study Limitations/Parameters	118
2. The Strengths of This Research.....	119
a. Measuring from the Center Points.....	119
b. Significance of Displacement in Criminal Investigations....	120
c. Following in the Footsteps of DNA Analysis	123
3. The Future of This Research	126
a. A Complete Population Study	127
b. Bacterial Analysis Combined with Displacement.....	127
c. The Courtroom’s View: Need to Eliminate Gray Areas	128
d. Additional Studies	132
e. Advances in Digital Technology	135
f. Formation of NIFS	137
F. Conclusion	139
V. BIBLIOGRAPHY	141
VI. APPENDICES	149
A. Appendix A	149
B. Appendix B.....	150
C. Appendix C.....	151

TABLES

Table 1	Bezier curve results.....	96
Table 2	Polynomial curve results.....	97
Table 3	Ellipse curve results.....	98
Table 4	Differences between curves.....	108
Table 5	Multivariate results from repeated measures analysis of variance for the center points of each tooth.....	112
Table 6	The mean, standard deviation and post-hoc results for displacement for each tooth.....	113

FIGURES

Figure 1 Photograph identifying the individual teeth marks on skin of a victim	16
Figure 2 Fractured front teeth of serial killer Ted Bundy	19
Figure 3 Bite mark in duct tape.....	20
Figure 4 Animal vs. human bite marks.....	22
Figure 5 Visible human bite mark on the abdomen of an infant	23
Figure 6 Computer reconstruction of an individual's dentition to a bite mark.....	29
Figure 7 Dental wax imprint of a mandibular arch.....	74
Figure 8 Dental wax imprint of a maxillary arch.....	75
Figure 9 Photograph of bite mark on human skin.....	76
Figure 10 Basic components of a cubic Bezier curve.....	77
Figure 11 Basic polynomial curve	79
Figure 12 Schematic view of an ellipse curve	80
Figure 13 Decision tree used for determining displacement	81
Figure 14 Wax exemplar.....	83
Figure 15 The mesial and distal aspects of a tooth for each exemplar	84
Figure 16 Four points defining the Bezier curve	87
Figure 17 Adjustment of 53% for the Bezier curve.....	88
Figure 18 Six points defining the polynomial curve.....	89
Figure 19 Three points defining the ellipse curve	90
Figure 20 The center point pixel on a tooth and its relationship to the curve.....	91
Figure 21 The center pixel point inside the curve on a tooth.....	92
Figure 22 The center pixel point outside the curve of a tooth	93
Figure 23 The angle used in the measurements	93
Figure 24 Digital technology applied to each curve	94
Figure 25 Box plot of tooth #23 for all three curves.....	100

Figure 26 Box plot of tooth #24 for all three curves	101
Figure 27 Box plot of tooth #25 for all three curves.....	102
Figure 28 Box plot of tooth #26 for all three curves.....	103
Figure 29 Box plot of tooth #7 for all three curves.....	104
Figure 30 Box plot of tooth #8 for all three curves.....	105
Figure 31 Box plot of tooth #9 for all three curves.....	106
Figure 32 Box plot of tooth #10 for all three curves.....	107
Figure 33 Box plot of displacement for all three curves.....	109
Figure 34 Individual value plot of displacement for all three curves	110
Figure 35 Histogram of displacement for the center points of the teeth.....	111
Figure 36 Kieser's geometric morphological analysis grid.....	134

CHAPTER 1: INTRODUCTION

Dental forensic science and the law in criminal cases have had a compatible, yet challenging, partnership for as long as crime has existed. Crime scenes are rich in information that reveals the nature of the criminal activity and the identities of the persons involved.¹ When dental forensic evidence is uncovered and analyzed, forensic experts attempt to uncover the actions or happenings of an event by way of identification, classification (or individualization), association, and reconstruction.² It is the patrons of forensic dentistry—the police, the attorneys, and the courts—who have conflicting expectations of what the science is likely to provide.³

Throughout world history, dental forensic science and the law have had many encounters that reflect their demanding expectations of each other. In numerous criminal incidents, the law has utilized the scope of analysis that dental forensic science has to offer. The relationship between the two disciplines has evolved to answer questions about the identity of human remains; thus, dental forensic science and the law have relied upon each other to solve crimes, with little doubt about their respective realms of expertise.

¹ National Research Council of the National Academies, “Strengthening Forensic Science in the United States: A Path Forward,” Washington, D.C.: National Academies Press (2009).

² Id.

³ David L. Faigman et al., Modern Scientific Evidence: Forensics, Student Edition Thomson West (2006): 381-444.

Dental Forensic Science and the Law: A Partnership

What started out as a partnership with qualitative objectives for discovering the truth, forensic dentistry and criminal law were conjoined and seemed made for each other. As human beings, we first identify each other by what we see physically. It is natural when talking with other people to notice teeth and compare their uniqueness to our own. Physics and logic determine that an object is unique.⁴ The simple observation of dental individuality sets the stage for the inevitable meeting between forensic dentistry and the law. It is the association of dental evidence that may link a person to a crime and may reconstruct the sequence of past events, creating a level of understanding for the courts to pursue. From ancient times to the present, history tells much about this link.

The roots of dentistry as a profession were discovered in the pyramids of Giza, Egypt. A skull from 2,500 B.C. was found with gold wire holding two molars together; however, the first dental findings used in a forensic manner were associated with Emperor Nero of Rome. The following scenarios depict the use of the initial principles of forensic dentistry: 1) Nero's mother, Agrippina, had her husband's (Emperor Claudius) mistress, Lollia, killed and her head brought to her for identification by means of a discolored tooth and by an abnormality of the teeth coming together, known as malocclusion; 2) Nero's mistress, Sabina, had Nero kill his mother, who was subsequently identified by two maxillary teeth; and 3) Sabina had Nero kill his first wife, who was identified subsequently by either a discolored tooth or malocclusion.⁵ Within

⁴ K. Imman and N. Rudin, "The Origin of Evidence," Forensic Science International 126: 1 (2002): 11-16.

⁵ James A. Cottone and S. Miles Standish, Outline of Forensic Dentistry. Chicago, IL: Year Book Medical Publishers, Inc. (1982): 22.

this complex web of murder lies the common thread of establishing identity through the purported uniqueness of the human teeth.

After the commission of a crime, the recognition of evidence and the processes that follow in a forensic investigation all result from decisions made and actions performed by people.⁶ While mere observation is a part of the scientific method, it often is not sufficient for legal recognition; however, in some cases, the dental forensic process stops at identification alone.⁷

Identification

As the preceding scenarios regarding Nero illustrate, the human teeth—and the unique marks they leave behind—historically and primarily have been used for identification purposes. A further example includes how William the First (the Conqueror) of England had an unusual malocclusion that allowed him to use his teeth to mark the wax of the official seal of England. This method of identification was significant after William overthrew King Harold in 1066.⁸

Centuries and continents apart, General Joseph Warren, a distinguished physician in Boston who was commissioned as a brigadier general in the Massachusetts militia, was killed during the 1776 Battle of Bunker Hill during the American Revolution. His body was stripped and buried by the British. Later, his remains were identified by American patriot Paul Revere because he had replaced one missing upper tooth for General Warren

⁶ Imman and Rudin, “The Origin of Evidence,” 11-16.

⁷ David L. Faigman et al., Science in the Law, American Casebook Series, St. Paul, MN: West Group (2002).

⁸ Cottone, Outline of Forensic Dentistry, 23.

with a piece of walrus tusk.⁹ This is an example of unique dental forensic evidence in identifying a specific person.

Whenever it is not possible to identify a deceased person due to incineration, decomposition or skeletonization, dental forensic identification is extremely reliable and the most practical method available.¹⁰ Dental forensic evidence, including even the smallest fragment of tooth material, has been used extensively in the identification of victims of crimes, persons missing in war-time action, and individuals missing after natural disasters.

The first major trial based largely on dental evidence used for identification involved Bostonian Dr. John Webster in 1850. Dr. Webster was convicted for murdering Dr. George Parkman, a wealthy benefactor of the Harvard Medical School. Webster was in debt to Parkman, and it is believed that Parkman demanded money when he suspected that Webster owed others money as well. After Parkman was murdered and dismembered, it was learned that his removable partial denture (made for him by Dr. Keep) was found behind the toilet with the remains of incinerated bone. Particularly interesting in this case, the partial denture was protected from incineration by the skull, which remained intact. The saliva in Parkman's mouth vaporized and kept the partial denture from exploding. Webster was convicted based on the testimony that used identification of the corpse in combination with a great deal of circumstantial evidence.¹¹

⁹ Id.

¹⁰ Steven C. Clark et al., "Medicolegal Death Investigator," Occupational Research and Assessment, Inc. (1996): 266-270.

¹¹ Robert Sullivan, The Disappearance of Dr. Parkman, Boston, MA: Little, Brown and Company (1971).

The military use dental forensic evidence as a mean for identifying the human remains of soldiers and those missing-in-action (MIA). On December 4, 1985, the Socialist Republic of Vietnam returned the remains of seven U.S. servicemen killed during the Vietnam War. With 2,400 MIAs, identification was facilitated by use of a computerized dental database developed by the Army.¹²

In addition to identifying murder victims and casualties of war, dental forensic evidence is used to identify multiple bodies recovered in the wake of disasters. In 1976, Colorado's Big Thompson Canyon flooded, stranding 1,500 of the 2,500 area residents. Military and civil personnel were able to recover 139 bodies and identify them with the aid of computers in analyzing dental evidence found at the disaster sites. In 1978-79, airline crashes including American Airlines Flight 191 out of Chicago's O'Hare Airport (274 dead) and Southern Airways in San Diego (144 dead) required the use of dental records to identify the human remains. In 1979, dental forensic evidence played a major role in identifying many of the 913 victims of the Jonestown massacre in Guyana.¹³

Currently, all cases using dental forensic identification for victims of a mass disaster have to be handled individually.¹⁴ After a mass disaster such as an earthquake, tsunami, plane crash or act of terrorism, forensic experts must compare each victim's records with scores of dental records in an attempt to make a proper identification. This can be a tedious, time-consuming process, taking months or even years, and mistakes can occur.

¹² Cottone, Outline of Forensic Dentistry, 26.

¹³ *Id.*

¹⁴ "New Automated System IDs Victims of Mass Disasters in Minutes," November 2007. <http://www.rsna.org>, (Last visited March 2010).

In 2006, researchers from the Graduate School of Information Sciences at Japan's Tohoku University¹⁵ took steps to address these problems. They developed a novel approach that speeds up the process and improves the accuracy of identifying individual dental records, thereby reducing the error rate. They developed an automated dental x-ray (radiograph) matching system¹⁶ named the Phase-Only Correlation or POC system. It has the ability to match dental records quickly, often taking less than four or five seconds to complete the process. The system uses a special image-matching technique, which aligns images, corrects any distortions, measures the similarity between images, and calculates a score regarding the image's likelihood of being a match. This data is then sent to a forensic expert for final examination. Instead of hundreds of x-rays, the computerized system typically narrows down possible matches to a handful of subjects for the forensic expert to consider. The POC proved to be incredibly reliable in tests on over 3,600 sets of dental records and shows promise for being used in the United States in the near future for criminal investigations as well as mass disasters.¹⁷

While mass disasters involve a finite number of people to identify and the availability of full dentitions of teeth from the victims as well as from radiographic images in dental records, bite mark cases offer different circumstances. Dental forensic scientists are challenged in their scope of identification to fewer numbers of teeth, a large number of potential suspects, and dental imprints in human flesh, which is not a stable medium.¹⁸

¹⁵ Id.

¹⁶ Id.

¹⁷ Akira Nikaido et al., "A Dental Radiograph Registration Algorithm Using Phase-Based Image Matching for Human Identification," *ISPACS (2006)*: 375-378.

¹⁸ Faigman, *Science in the Law*, 1-65.

Therefore, forensic individualization (or classification) sciences are important for the analysis of human bite marks in criminal investigations.

Classification/Individualization

Classification or individualization of evidence involves narrowing the class characteristics to one. In the comparison process, class characteristics serve to screen a large number of items by eliminating from consideration those items that do not share the characteristics common to all of the members of that group. Class characteristics do not establish uniqueness; however, individual characteristics are those exceptional characteristics that may establish the uniqueness of an object.¹⁹ These serve to identify a particular member of the group. For bite marks, a tooth mal-position or diastema (space) can produce individual characteristics that allow the dental forensic scientist to eliminate, narrow down or identify suspects depending on their degree of distinctiveness.²⁰ Here lies the strength— or weakness— in the dental evidence process. Individual characteristics of teeth must be defined and quantified before an individual's dental pattern can be acknowledged as unique in bite mark analysis. Then, empirical studies are needed to prove the validity and reliability regarding the individuality in the human dentition by the dental forensic expert.

Though dental forensic science may never “deliver the exactitude of the mathematical sciences”²¹, the courtroom has come to expect an empirical answer or gold standard in bite mark analysis that offers both reliability and validity. Reliability is the extent to which measuring instrument produces the same results when it is used

¹⁹ Faigman, Modern Scientific Evidence: Forensics, 5.

²⁰ Mark L. Bernstein, “Nature of Bitemarks,” Bitemark Evidence, New York, NY: Marcel Dekker (2005): 59-80.

²¹ I. R. Hill, “Evidential value of bite marks,” Forensic Odontology (2000): 93.

repeatedly to measure the same object or event. Validity refers to the degree to which a measuring instrument measures what it purports to measure.²² The dental forensic science community has escalated its efforts to provide technical and sophisticated means with accuracy and repeatability to that end; however, the legal system wants more than standards and guidelines. Moreover, lawyers want what is in the best interest of their clients' outcome, no matter how inexact the dental forensic science may be. It is when legal issues are decided by scientists, or science issues are decided by lawyers, that difficulties arise.²³ This has led to the modern-day problematic partnership between dental forensic science and the law. Once very supportive in identifying victims on the basis of their dental condition, the partnership is struggling with litigators scrutinizing and arguing the validity and reliability of dental forensic evidence if it does not favor a client's case.

It appears the law sees DNA as the gold standard.²⁴ A "gold standard" is defined as a model of excellence or perfection of a kind.²⁵ The dental forensic scientist strives to achieve this standard by discovering the ultimate method for other experts to follow to establish the same, or near as same results, for affirming or negating a response to their research questions. The forensic question of "Whose bite mark is it?" is often compromised by disagreement among experts as to the original source of the bite mark based on the results of their analyses of the association of all the common sources.

²² Faigman, Modern Scientific Evidence, 45.

²³ P.D. Barnett, Ethics in Forensic Science: Professional Standards for Practice of Criminalistics, Boca Raton, FL: CRC Press (2001): 13.

²⁴ Michael J. Saks and Jonathan J. Koehler, "The Coming Paradigm Shift in Forensic Identification Science," Science Magazine 309 (August 5, 2005): 892-895.

²⁵ Gold Standard, The American Heritage® Dictionary of the English Language. 4th Ed. Houghton Mifflin Company, (2004).

Association

The concept of association infers physical contact between the “source” of the evidence and the “target.”²⁶ In other words, association links a person who bites another person or object in a crime. Association involves an evaluation of all the evidence. It is fundamental to a criminal investigation to treat a suspected bite mark as a bite mark until proven otherwise. If this evidence is not clearly evaluated, a valid analysis cannot be provided. Bite marks made before, during and after a sexual attack will normally cause some type of wound on the victim. The sadist, who bites his victim slowly and intentionally, can leave wounds that appear as bruises caused by other means. These marks must be considered significant, as they may prove a relationship between the victim and the perpetrator.²⁷ In 1967, 14-year-old Linda Peacock’s nude body was found with a bite mark on the breast. Along with other evidence, the bite mark led to the conviction of a young man in 1968.²⁸ Today, however, without strong empirical studies, opinion testimony of a dental match or no dental match alone would be challenged in the courtroom. In the *Peacock* case, the dental forensic scientist examined the bite mark evidence on Linda’s body to compare to the dental evidence (teeth) belonging to the suspect. It is fundamentally important to law enforcement to associate the biter with the crime or person(s) involved in a crime; otherwise the bite mark serves no useful purpose. This often leads to the last phase of solving the crime.

²⁶ Imman, “The Origin of Evidence,” 11-16.

²⁷ E.H. Dinkel, Jr., “The Use of Bite Mark Evidence as an Investigative Aid,” Journal of Forensic Science (November 1973): 535-547.

²⁸ Cottone, Outline of Forensic Dentistry, 25.

Reconstruction

Attempting to understand the sequence of past events in a crime reflects the reconstruction concept in the origin of evidence. This attempts to answer the “who, what, when, where and how” of a crime. The basic question is: “What role did the suspect and victim play or not play in the crime?” Bite marks from an attack may be present on the victim or on the perpetrator. Bite marks found on perpetrators are caused by the front teeth of the victim biting the assailant in self-defense.²⁹ They are often found on the hand of the assailant as an attempt is made to stifle the outcry of the victim. These bites can be quite severe, causing a wound as the victim bites quickly and in a haphazard manner.³⁰ While the physical evidence can reconstruct the “who, what, when, where and how” of a criminal case, the “why” is not typically answered by the physical evidence.³¹

The preceding concepts— identification, classification/individualization, association and reconstruction—form the infrastructure for the practice of forensic science and relate to the recognition, analysis and interpretation of the physical evidence.³² The court system often is skeptical of research that is directed toward a particular case, and this circumstance has frustrated many dental forensic scientists; however, they must address the reliability and validity issues in their scientific methodologies first, and remain tireless in their pursuit to be clearly understood by those in the law who question their knowledge and legitimacy.

²⁹ J. Furness, “Teeth Marks and their Significance in Cases of Homicide,” *Journal of the Forensic Science Society* 9 (1969): 169.

³⁰ Dinkel, “The Use of Bite Mark Evidence as an Investigative Aid,” 535-547.

³¹ Imman, “The Origin of Evidence,” 11-16.

³² *Id.*

Statement of the Problem

The adversarial trial system in the United States wants simple, inexpensive and fast answers to forensic science questions involving bite mark evidence based on sound, scientific principles. The stated goals of modern evidence law are to ensure “that the truth may be ascertained and proceedings justly determined.”³³ It is necessary to have an understanding of the law and dental forensic science issues in order to lay a foundation for a renewed, more compatible partnership that relies upon bite mark analysis.

The probability of a dental pattern observed in bite mark evidence matching a suspect’s dentition has not been quantified with valid and reliable methods. Oftentimes, a bite mark case is fairly straightforward. Photographs and dental casts from impressions of a suspect’s teeth are shown to a jury with little ambiguity. The quintessential question is whether the likelihood of another person’s bite could be an equally good match. In other cases where dental forensic scientists have had to convince the court of the legitimacy of their opinions, unresolved debate has ensued to question the validity of their facts. The fundamental problem lies in the different ends sought: the goal of forensic science is, in Faigman’s words “the production of the truth”, whereas “the goal of law is the achievement of justice”.³⁴

In years past, the court system has been interested in the means to identify bodies and suspects, not the validity and reliability of the dental forensic science behind the results. On the other hand, dental forensic science has been concerned with establishing from the testimony of dental experts whether specific dental characteristics could determine individual uniqueness. The critical question dental science must address is

³³ Federal Rule of Evidence, 102.

³⁴ Faigman, Modern Scientific Evidence: Forensics, 4.

whether tooth characteristics in the human dentition can be scientifically measured with validity and reliability and contribute to human uniqueness. It is with the development of digital technology that new research will be able to support this endeavor.

The use of digital technology in the forensic sciences has made a significant impact on the validity and accuracy in measuring spatial variables in criminal evidence. Increased access to software programs, such as Adobe Photoshop® and specially constructed spatial algorithms, has provided forensic scientists with the means to develop simple and reliable methods to evaluate dental characteristics. Use of imaging technologies that ensure repeatability and allow for documentation of performance checks and corrective actions with equipment and systems are imperatives within the criminal justice system with regard to bite mark analysis.³⁵

In terms of a scientific basis, bite mark analysis is based on expert interpretation that has yet to be fully validated according to rigorous, objective methods. The influential 2009 report *Strengthening Forensic Science in the United States: A Path Forward*³⁶ by the National Research Council (hereinafter, “NRC report”) found that no studies have been conducted of large populations to establish the uniqueness of marks or features in a variety of forensic disciplines, including bite marks. A statistical framework that allows quantification of these unique dental features is needed. The standardization and clarification of the terminology used in reporting and testifying the

³⁵ SWGIT, “Guidelines for the Use of Imaging Technologies in the Criminal Justice System,” Guidelines for the Forensic Imaging Practitioner Version 2.3 (June 6, 2002): 1-7.

³⁶ National Research Council of the National Academies, “Strengthening Forensic Science in the United States: A Path Forward,” Washington, D.C.: National Academies Press (2009).

scientific methods in bite mark analysis and many other forensic disciplines are considered necessary.

The first step in the scientific method is to define what is to be observed. Though this may seem basic, it is the first chance for the research to be misinterpreted. That said, the research in this study will define tooth displacement and provide an analytical methodology that is repeatable for any examiner to use. Little rigorous systematic research has been done to validate the basic premises and techniques in dental forensic science.³⁷ The NRC report recommends the use of automated techniques capable of enhancing forensic technologies and permitting the replication of results for later verification.³⁸ This research study utilizes computer software programs that are widely available to discover scientific facts and methods useful for the law.

DNA analysis has set the bar higher for other forensic science methodologies because it has provided a tool with a higher degree of reliability and relevance than any other forensic technique. Bite mark analysis has become the established process that has proved successful in many criminal cases. The challenges lie in the interpretation of the bite mark analysis, the characteristics of the object that is bitten and the process of biting.³⁹ Bite mark analysis must strive to reach the same high standard of DNA analysis and overcome problems in order to be accepted by the court system with any degree of credibility. Communication along with scientific rigor, therefore, will be the critical elements in an attempt to resolve the challenges in the partnership between dental forensic science and the law.

³⁷ Id. at S-16.

³⁸ Id. at S-17.

³⁹ Hill, "Evidential Value of Bite Marks," 93.

CHAPTER 2: DENTAL FORENSIC SCIENCE ISSUES

Essential to the field of dental forensic science are the collection of dental evidence, the dental testimony presented before a jury, and ultimately, the individuality of the dental evidence. Before examining each of these, the role of the dental forensic scientist is to deal with proper handling and examination of dental evidence and proper evaluation and presentation of dental findings in the interest of justice. The expertise of the dental forensic scientist is utilized for: (1) the diagnostic and therapeutic examination and evaluation of injuries to jaws, teeth and oral soft tissues, (2) the identification of individuals, especially casualties in criminal investigations and/or mass disasters, and (3) identification, examination and evaluation of bite marks that occur with some frequency in sexual assaults, child abuse cases and personal defense situations.⁴⁰

Evidence Collection

Dental forensic evidence can be found anywhere. Crime scenes should be thoroughly inspected for food, cigarette butts, pencils, chewing gum or any other materials that may contain bite marks left by a criminal suspect. Any disturbance in handling the evidence will make later comparisons difficult or impossible. Securing the crime scene and leaving food items undisturbed is essential to avoid problems for the forensic team of investigators.⁴¹

Most often a police officer is the first to come in contact with a bite mark victim. The officer may fail to discover such evidence, especially if a living victim is ashamed to

⁴⁰ Glenn N. Wagner, "Scientific Methods of Identification," Forensic Dentistry, (1997): 2.

⁴¹ Mary G. Leary, "Proof of Identification of Bite Marks," American Jurisprudence 3rd Edition (October 2003).

reveal a bite mark in a private area of the body. In other circumstances, it is not unusual for evidence to go undetected because the crime scene's location and environment can obscure visible details. For example, bite mark(s) could be covered with blood, clothing or debris. Or, in the case of deceased victims, a bite mark might be too subtle to be recognized until changes resulting in decomposition define the mark's existence. Law enforcement officers might also overlook the significance of bite mark evidence if a victim is able to identify the assailant visually.

Bite marks are important evidence in criminal investigations because a comparison of bite marks contributes to the elimination of a suspect or suspect(s). In addition, the bite mark analysis represents a credible and reliable component of the forensic investigative process. Yet in order for such evidence to be fully utilized, the following are essential: (1) law enforcement personnel must understand the science of bite mark analysis, (2) dental schools must educate students in the field of forensic study, and (3) legal questions related to bite mark evidence collection and analysis should be clarified through the court system.⁴²

The collection of dental forensic evidence involves three processes: (1) a description of the bite mark(s), (2) collection of evidence from the victim, and (3) collection of evidence from the suspect(s).⁴³ Vital information during the collection process includes demographics, location of the bite mark(s), and the shape, color, size and type of injury. Washing, contamination, lividity, embalming, decomposition and changes in position can affect bite marks. During the collection of dental evidence, bite marks should be photographed and swabbed for DNA and blood type. (Figure 1) Dental

⁴² Dinkel, "The Use of Bite Mark Evidence as an Investigative Aid," 535-547.

⁴³ Larry A. Barry, "Bite Mark Evidence Collection in the United States," 21-26.

impressions need to be made and tissue samples must be taken in cases of homicides. Necessary search warrants, court orders or legal consent must be obtained prior to collecting bite mark evidence from a suspect. This can include photographs, extra- and intra-oral examinations, impressions, sample bites and cast models.⁴⁴

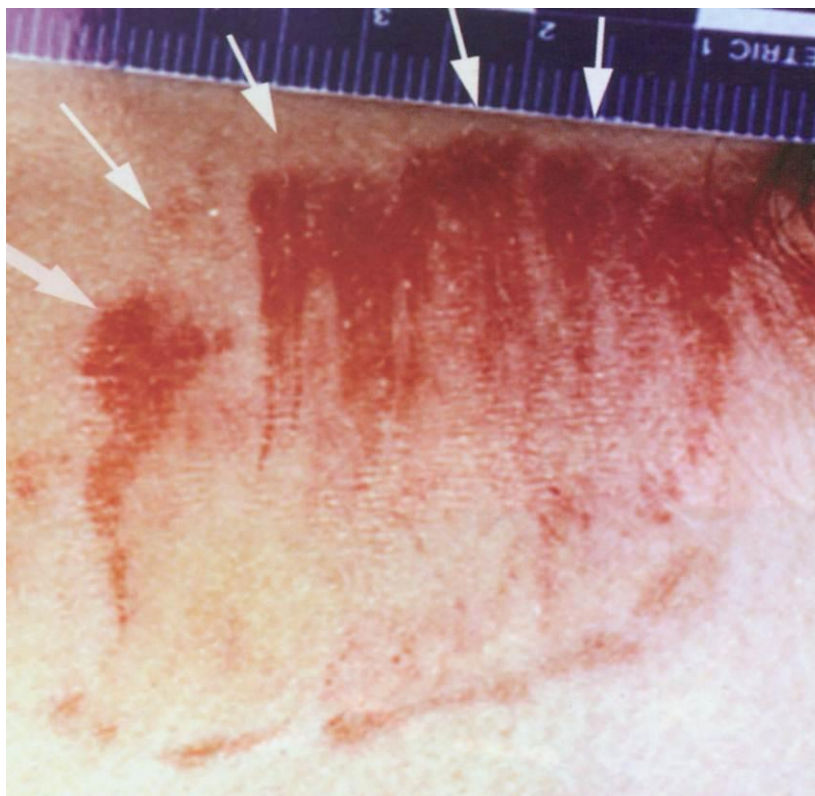


Figure 1: Photograph identifying the individual teeth marks on skin of a victim
(Courtesy of C. Michael Bowers)

A strict protocol implemented in 1984 by the American Board of Forensic Odontology (ABFO) assured fairness and accuracy in the collection of bite mark evidence. The standards were established to enable the dental forensic scientist to use a standard scale for accurate reproductions of the actual bite mark.⁴⁵ When used in legal

⁴⁴ Barry, "Bite Mark Evidence Collection in the United States," 24.

⁴⁵ Dinkel, "The Use of Bite Mark Evidence as an Investigative Aid," 535-547.

proceedings, good dental forensic science scrutinizes its own collection approaches to maintain the integrity of the dental evidence.

Dental materials and the methods to collect and evaluate bite mark evidence have evolved over the years. In 1963, silicone impressions were used in addition to plaster impressions because of the flexibility and elasticity of the material.⁴⁶ Water-based impression materials as alginates are not recommended since they are not dimensionally stable, must be poured immediately, and the impressions cannot be preserved undistorted.⁴⁷ In the 1970s, ultraviolet photography was introduced, followed by radiography and videotape analysis.⁴⁸ Later in the 1980s, collection of dental forensic evidence introduced salivary swabbing for blood typing techniques and, eventually DNA analysis from forensic samples.⁴⁹

Today, access to digital photography and computer technology has enhanced the already sophisticated process of collection and analysis of bite mark evidence. Bite mark cases, however, are still confounded by: (1) the anatomic site that is bitten, (2) the biology of the skin, (3) the posture of the victim during the biting process and (4) the poor bruising detail of the bite injury on skin.⁵⁰ Yet justice prevailed with the assistance of dental forensic scientists in the highly publicized serial murder case of Ted Bundy.

⁴⁶ Barry, "Bite Mark Evidence Collection in the United States," 24-25.

⁴⁷ L. Thomas Johnson, "The Suspect," Bitemark Evidence, New York, NY: Marcel Dekker (2005): 419.

⁴⁸ Barry, "Bite Mark Evidence Collection in the United States," 24-25.

⁴⁹ Id.

⁵⁰ Michael Bowers, "The Balance of DNA and Bite Marks: A Lawyer's Point of View," Forensic Odontology (2000): 99-107.

In July 1979, Ted Bundy was convicted for entering a sorority house in Florida, where he murdered two co-eds and attempted to murder two others. He then entered a nearby home and bludgeoned a third female victim. It was discovered that bite mark evidence was left on the body of one of the victims and that the biter had poorly aligned teeth. This evidence helped to establish probable cause necessary to obtain a search warrant to take dental impressions, bite records and photographs of Ted Bundy's dentition. Three dental forensic examiners implicated Bundy as the perpetrator of the crime using computer-enhanced images of the bite pattern. He was convicted of the crime and eventually executed for the murder of a 12-year-old girl in another case. He was one of the most notorious serial killers in U.S. history, reportedly responsible for the deaths of as many as 36 young women from Florida to the State of Washington. After the nation observed how the dental forensic examiners explained the nature of bite mark evidence to a jury in this highly publicized case, the legal profession and general public became much more aware of the admissibility of bite mark evidence.⁵¹

Dental Testimony

Historically, the reliability of expert testimony regarding evidence in criminal cases has been important. The Emperor Justinian in Constantinople established the Justinian Code in 528 A.D., which provided for the appointment of friends of the court to advise judges on matters that required specialized knowledge. Emperor Charlemagne in 800 A.D. required expert testimony reflecting "proofs as clear as day" for cases where a man's life was at stake for crimes of rape and physical injury.⁵² Clearly, the criteria for

⁵¹ Gerald L. Vale, "History of Bitemark Evidence," Bitemark Evidence (2005): 16.

⁵² Bernstein, "Nature of Bitemarks," 59-80.

experts in the aftermath of the Roman and Holy Roman empires differed greatly from modern U.S. trials involving dental testimony. Today's dental forensic experts provide testimony rooted in scientific methodology that strives to be objective concerning a most subjective and unique object of study.

Specifically, the dental forensic scientist analyzes the unique characteristics of the human dentition in various stages. The adult human dentition consists of 32 teeth, each with its own characteristics, size and shape. The dental forensic scientist records all restorations, anomalies, and missing teeth as well as radiographic and photographic recordings of the dental arches. In the case of a deceased victim, the findings are compared with ante mortem dental records and radiographs to effect positive identification. The assessment requires age and gender determination. This information can be ascertained by skeletal structures, dental eruption patterns, restorative materials in the teeth, status of the periodontium (supporting structures of the teeth) and serology as well as cytology (cellular characteristics) of the pulp, saliva, and mucosa (the membrane that lines the inside of the mouth).



Figure 2: Fractured front teeth of serial killer Ted Bundy (Courtesy of Dr. Richard Souvrons.)

Because of extractions, malalignment, malposition, malformation, spacing, fractures (Figure 2), dental restorations and numerous other factors, the human dentition appears quite individual.⁵³ Thus, when a person bites an object, he/she usually leaves a unique dental pattern. Normally, when a person bites into an object (e.g. duct tape in Figure 3), the upper teeth hold the object while the lower teeth do the actual cutting.⁵⁴ This provides valuable information with regard to the alignment of teeth and the size and form of the dental arch.⁵⁵ All of these factors are considered in bite mark analyses for dental forensic testimony.



Figure 3: Bite mark in duct tape. (Courtesy of C. Michael Bowers.)

⁵³ Dinkel, “The Use of Bite Mark Evidence as an Investigative Aid,” 536.

⁵⁴ Id.

⁵⁵ Dinkel, “The Use of Bite Mark Evidence as an Investigative Aid,” 535-547.

Scientific research must show that analyses used by dental forensic scientists are “reliable,” “valid,” “accurate” and “precise.”⁵⁶ Reliability refers to the extent to which a measuring instrument produces the same result when it is used repeatedly to measure the same object or event; validity is the degree to which a measuring instrument measures what it is supposed to measure; accuracy implies conformity to a standard; and precision reflects the refinement of a measure.⁵⁷ While the dental forensic scientist has an obligation to express his/her testimony in the courtroom in the clearest manner possible, problems stem from communicating the relative certainty of the scientist’s findings.

These findings or conclusions are reached based upon the similarities of the teeth to the injuries caused by various teeth of a suspect or that of a victim of an attack when used as a weapon of self-defense. Inanimate objects, such as food, chewing gum, cigarette butts, duct tape, pencils and other items of physical evidence discovered at the crime scene will sometimes contain imprints of teeth.⁵⁸ The range of possible conclusions resulting from bite marks analysis includes: (1) positive identification, (2) probable identification (more likely than not), (3) possible identification (cannot exclude), (4) insufficient data available (inconclusive), and (5) negative identification (exclusion).⁵⁹ With bite mark analysis being widely accepted by the courts, the validity and scientific basis for its use as evidence have frequently been challenged during trials. The lack of standards for collection and use of bite mark evidence continues to be scrutinized.⁶⁰

⁵⁶ Faigman, Modern Scientific Evidence: Forensics, 18.

⁵⁷ *Id.*

⁵⁸ Bernstein, “Nature of Bitemarks,” 59-80.

⁵⁹ Faigman, Modern Scientific Evidence, 438-442.

⁶⁰ C. Michael Bowers, Forensic Dental Evidence. San Diego, CA: Elsevier

Issues of Individuality

Where humans have left their dental imprint behind, dental forensic scientists have had to make *objective* observations while relying on *subjective* interpretation of the meaning of dental patterns in determining individuality. Bite marks can be human or animal, and there are stark differences that even the layperson can detect. Notice in Figure 4 how animal bite marks have six incisors and two large canine teeth compared to the human bite mark, which has four incisors and small canines.⁶¹

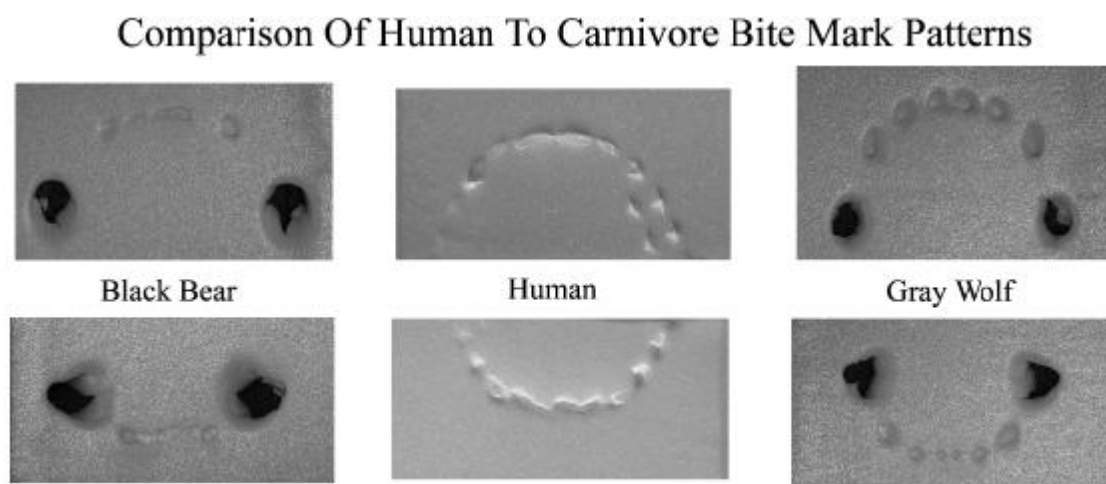


Figure 4: Animal vs. human bite marks (Courtesy of Denise C. Murmann.)

Shape and location of bite marks add elements of individuality as well. Bites usually appear as oval or circular contusions, bruises or abrasions. In some cases, indentations or lacerations are made by specific teeth on the skin surface. Most human bites exhibit markings from the four upper and/or four lower anterior (front) teeth and the four canine teeth. Animals more often bite the extremities, such as feet, legs, hands and

Academic Press (2004).

⁶¹ Denise C. Murmann et al., "A Comparison of Animal Jaws and Bite Mark Patterns," Journal of Forensic Science 51:4 (July 2006): 846-860.

arms. Human bites are typically found on the breasts, abdomen, thighs, back, shoulders, nose, ears and fingers.⁶²

Most human bite marks are evident in crimes that include murder, assaults of a sexual or non-sexual nature, as well as elder and child abuse.⁶³ (Figure 5) Child abuse victims display bite marks that are often made in a rapid, random and enraged manner, resulting in tissue laceration; the marks are often distributed over a diffuse area and offer poor detail of the dentition.⁶⁴ Thus, the process of collecting dental evidence can be crucial to any criminal investigation.



Figure 5: A visible human bite mark is shown on the abdomen of an infant. Notice the two U-shaped curves that make up the oval shape. (Courtesy of C. Michael Bowers.)

⁶² Michael Bowers, Forensic Dental Evidence, 80.

⁶³ David Sweet, "Human bite mark evidence" Forensic Odontology. Belgium: Leuven University Press (2000): 76.

⁶⁴ Id.

It is important at this juncture to examine the “big picture” regarding current forensic literature which has relevancy for bite mark evidence and advances the need to describe the variable of displacement of the anterior teeth in the human dentition.

Current Literature Regarding Reliability and Validity

Current literature involving bite marks examines a variety of issues including: (1) scientific methods and techniques, (2) credentials of dental experts, (3) the role of DNA in the development of quantitative methods in bite mark analysis, and (4) the advances of digital software features for computer-aided image analysis. All contribute to a greater understanding of the potential reliability and validity of bite marks with regard to meeting a minimum level of acceptability for judicial inquiry in criminal investigations.

Scientific Methods and Techniques

Current scientific methods in bite mark analysis involve the formulation of a theory followed by rigorous testing to either confirm or disprove the theory. Such an investigation is both a qualitative and quantitative evaluation aimed at evaluating the use of “opinion” regarding a dental pattern.⁶⁵ The opinion and testimony given in court should include objective testing. In order to be reliable and persuasive, the testing should include an analysis of opposing and alternative theories.⁶⁶

Objective scientific testing uses accepted and replicable methodologies and analyzes all the relevant facts of a specific dental pattern in a criminal investigation. Tests that fail to acknowledge prominent facts and use questionable methodologies may be quickly ruled inadmissible by a judge. Forensic tests that are developed and

⁶⁵ Robert B.J. Dorion, Bitemark Evidence, New York, NY: Marcel Dekker (2005).

⁶⁶ Richard A. Mincer and Harry H. Mincer, “Science and the Law,” in Bitemark Evidence, New York, NY: Marcel Dekker (2005): 465-475.

performed for use outside of the courtroom are more persuasive with a trial judge than those specifically created for legal purposes.⁶⁷

During the last ten years, dental forensic sciences has come under fire, and numerous studies in bite mark research have involved comparison overlays in an attempt to satisfy the courts of the rigor and objectivity of such analysis. The American Board of Forensic Odontology (ABFO) initiated guidelines and standards for bite mark evidence in 1986 that are widely used today. Proper dental forensic evidence collection methods are readily adhered to by the majority in the dental forensic community, however, bite marks analysis methodologies are not.⁶⁸

Without access to complex laboratory equipment or the use of human volunteers, bite mark research is difficult because it does not provide authentic forensic material for analysis. Bite mark analysis is one of the most contentious issues in forensic dentistry among the dental experts who testify in criminal investigations. To produce evidence-based, scientific research in bite mark analysis, the testing should be standardized, replicable and promote the best standard of practices.⁶⁹ The challenges for dental forensic experts is to make this subject comprehensible such that juries can easily understand the analysis being performed and so that essentially untrained personnel can readily duplicate the analysis and results.

Credentials of Experts

The legal system assumes the dental forensic researcher is searching for the truth as to whether a cause and effect relationship occurred between a biter and a victim or

⁶⁷ Mincer and Mincer, "Science and the Law," 465-475.

⁶⁸ Faigman, Modern Scientific Evidence: Forensics, 425.

⁶⁹ Iain A. Pretty, "Unresolved Issues in Bitemark Analysis" in Bitemark Evidence, New York, NY: Marcel Dekker (2005): 547-563.

object. The dental forensic expert is allowed to give testimony to assist the jury and judge in understanding the bite mark evidence in terms of relevancy and reliability. Judges, as the gatekeepers of due process, decide whether to admit an expert's testimony based on the research's integrity (i.e., is the analysis biased or flawed?). Judges must ensure that bite mark analysis meets the criteria for rational and sound forensic testing so that juries will hear impartial and objective testimony from dental forensic experts.⁷⁰ The judicial culture continues to emphasize methodological rigor, openness and cautious interpretation of data from its experts. Some individuals contend the disparity in credentials alone creates a different set of prevailing norms, leading courtroom experts to overstate or fabricate their findings.⁷¹

In forensic science alone, 96 percent of practitioners hold a bachelor's degree or less, 3 percent have a master's degree and 1 percent holds doctorates. Based on case analysis data provided by the Innocence Project, forensic testing errors accounted for 63 percent of the factors associated with wrongful convictions in 86 DNA exoneration cases. In those cases, 27 percent of the forensic scientists gave false or misleading testimony.⁷² As a result, skepticism has fueled the push to eliminate traditional forensic science approaches that can be plagued with subjective interpretation and propel a pull toward the more powerful objective evidence of DNA analysis.

Role of DNA

Dental forensic scientists believe there is a transformation underway toward more empirically-grounded science in their approaches. DNA technology has brought this to

⁷⁰ Fed. R. Evid. 702 advisory committee's note (2000).

⁷¹ Saks and Koehler, "The Coming Paradigm Shift in Forensic Identification Science", 892-895.

⁷² Id. at 893.

the forefront and has become a model of sound identification science because its approach is derived from core scientific disciplines. The courts have reinforced this transformation by scrutinizing the techniques used by dental forensic experts in individual cases. DNA typing provides data-based, probabilistic assessments of the meaning of evidentiary matches.⁷³ This represents an advance over potentially misleading match/no-match claims made by forensic dental experts using bite mark evidence.⁷⁴ A real strength to DNA typing is its statistical approach based on population genetics theory and empirical testing. The major challenge facing the future of bite mark analysis is development of objective probabilistic measures from complex images.⁷⁵

Cases involving DNA analysis have acted as an independent means to support or refute a bite mark opinion. In some instances, DNA corroborated bite mark identification and in others, it demonstrates the subjectivity of the bite mark evidence and cannot solely give a conclusive answer to the question of “Who made this bite mark?”

⁷³ Id.

⁷⁴ Id.

⁷⁵ Id.

Advances in Digital Imaging

Modern computer technology has allowed dental forensic investigators to recreate bite marks and human dentitions to determine possible suspects. This has significantly improved the objectivity of bite mark analysis in criminal investigations. A computer reconstruction of a dental arch is shown in Figure 6 from a case involving dental forensic scientists who collaborated with police in 2003 to solve a triple homicide using advanced imaging techniques.

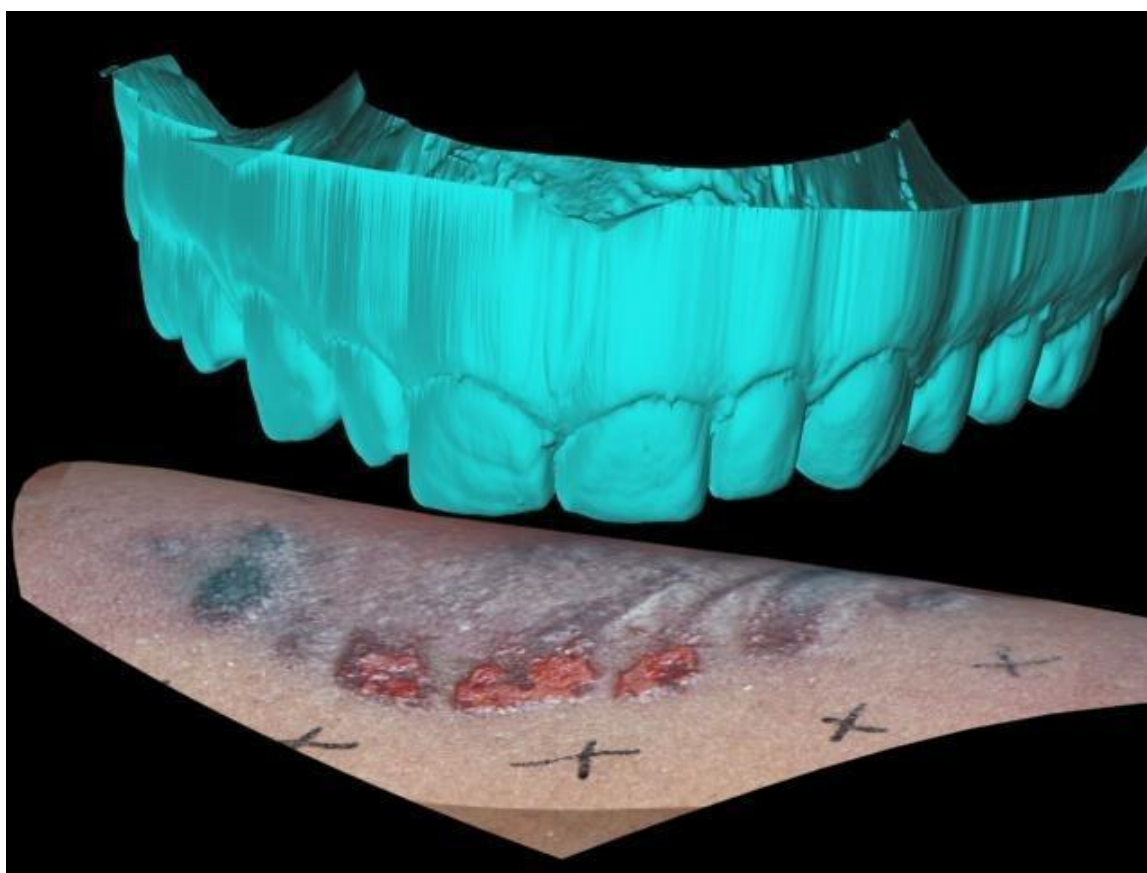


Figure 6: Computer reconstruction of an individual's dentition compared to a bite mark.
(Courtesy of Institute of Forensic Medicine, Univ. of Bern)

Three women were found beaten to death in an apartment outside of Zürich, Switzerland. One victim had a bite mark on her shoulder. After creating dental casts and using 3-D

imaging technology to recreate the bite sequence, dental forensic scientists were able to prove to a jury that the suspect made the mark. Consequently, the suspect was found guilty.⁷⁶

When a bite imprint is made in certain materials, identifiable marks show the morphology and arrangement of the anterior teeth in an arch form. These identifiable marks possess detailed variables that may have a high or low frequency of occurrence in the general population. Dental forensic scientists interpret a bite injury qualitatively by associative comparison to similarities and dissimilarities within the human dentition.⁷⁷ This kind of testimony has led to questions of reliability.

The use of computer-generated analysis offers potential for more objectivity and less subjectivity in dental forensic sciences. Various digital imaging techniques and software programs are used today to improve upon forensic analysis in criminal investigations. Even a print of a human ear is a concept being studied and measured with digital software to distinguish individuals. The computer can draw an ellipse on an earprint and provide numerical descriptions in earprint analysis to be used in criminal identifications.⁷⁸ Such digital technology has given rise to innovative forensic approaches and methods, offering significant advantages for bite mark analysis and methodologies.

⁷⁶ www.nlm.nih.gov/visibleproofs/galleries/technologies/virtopsy.html
(Last visited March 2010).

⁷⁷ P. Nambier, T.E. Bridges and K.A. Brown, "Quantitative Forensic Evaluation of the Bite Marks with the Aid of a Shape Analysis Computer Program," Journal of Forensic Odontostomatology 13:2(1995): 18-32.

⁷⁸ G.N. Rutty, A. Abbas, and D. Crossling, "Could Earprint Identification Be Computerised? An Illustrated Proof of Concept Paper," International Journal of Legal Medicine 119 (2005): 335-343.

Since the courts have taken an aggressive position regarding the acceptability of the scientific methodology used in a dental forensic expert's testimony, advances continue to be made in the physical and metric analysis of a suspect's bite pattern. In 1998, two forensic scientists tested the most common overlaying methods and showed there were significant differences between the techniques for both the area and rotation of teeth. These computer-based methods included hand-traced overlays from stone casts, hand-traced overlays from wax impressions, hand-traced overlays from xerographic images and the radiopaque impression method. The results determined that a computer-based production method was accurate and objective to use. It became the gold standard for measuring the precision of bite mark overlay production methods for criminal investigations.⁷⁹

The validity and reliability of scientific techniques used in the courtroom have brought many previously accepted methods of forensic investigation under closer inspection. Years and oceans apart, two more computer-based techniques were evaluated for their benefit and ease of use in bite mark analysis. The first included a "Magic Wand" tool that has been utilized in North America to create an outline of the perimeters of the biting surfaces of each tooth as the wand is placed in the mouth. The second technique involved development by Europeans utilizing a "Glowing Edge"TM filter that independently selects and highlights the edges of the cast and teeth from a suspect. These digital techniques are reliable methods to assess tooth position in bite mark overlays and

⁷⁹ David Sweet and C. Michael Bowers, "Accuracy of Bite Mark Overlays: A Comparison of Five Common Methods to Produce Exemplars from a Suspect's Dentition," Journal of Forensic Science 43:2 (1998): 362-367.

demonstrate that some of the examiners “simply followed the curvature of the teeth to produce a general outline of the arch.”⁸⁰

The objective of the comparison study was to evaluate these two newer techniques and their comparative reliability among board-certified forensic odontologists, forensic dentists and second-year dental students. Using either of the computer-based techniques, the results showed that the level of forensic experience did not account for differences in computer overlays produced by the various groups; however, the investigation did not evaluate the ability to analyze bite mark overlays. The lack of standardization of the computer software and hardware programs led to significantly different findings among the groups of examiners.⁸¹ Newer versions of digital software programs continue to evolve, and dental examiners will need to utilize these new technologies if forensic testimony is going to reap all of the potential benefits of bite mark analysis.

⁸⁰ Anne McNamee, David Sweet and Iain Pretty. “A Comparative Reliability Analysis of Computer-Generated Bitemark Overlays,” Journal of Forensic Science 50:2 (March 2005): 400-405.

⁸¹ Id.

CHAPTER 3: LEGAL ISSUES

In order to fully explore the partnership between forensic dentistry and the law, it is important to establish fundamental principles from each field. This chapter will begin with a brief overview of evidence law and proof in the modern adversarial trial followed by the constitutional limitations on the collection of evidence pertinent to bite mark analysis. It will then discuss the various standards of admissibility that govern expert opinion testimony generally and bite mark analysis in particular. The most basic legal parameters involved in this study surround the many facets of evidence, which ultimately leads to constitutional issues that date back to the founding of the United States.

Modern Evidence Law Generally

The law of evidence governs how parties, judges, and juries offer and then evaluate the various forms of proof at trial.⁸² Generally, evidence law establishes a group of limitations that courts enforce against attorneys in an attempt to control the various events that the trial process presents in an adversarial setting. In the United States, the federal courts must follow the Federal Rules of Evidence (FRE) while state courts follow their own rules, many of which are based on various iterations of the FREs.⁸³

The FRE, thus, has been enormously influential in the development of evidence law in American courts. This influence in part is a result of its brevity and simplicity. Before 1975, evidence law was mostly a creature of the common law tradition.⁸⁴ Judge-made rules dominated issues of admissibility supplemented by scattered statutes, state and federal. The FRE was drafted and proposed by a distinguished advisory committee

⁸² Giannelli, Understanding Evidence 2d ed. Newark, NJ: LexisNexis (2006), 4.

⁸³ *Id.* at 10.

⁸⁴ *Id.* at 4.

composed of practitioners, judges and law professors appointed by the United States Supreme Court.⁸⁵ Just 20 years after the federal judicial system adopted the FRE, over three-quarters of the states had adopted codes that closely resemble the federal model, although a number of important jurisdictions have rejected its template.⁸⁶ The FRE applies in all federal courts in both criminal and civil cases.⁸⁷ Understanding some of the basic provisions of the FRE enables us to better understand the proof processes at trial and how law shapes, and sometimes distorts, science in the courtroom.

Admissibility of Evidence

Evidence comes in the forms of tangible objects and witness testimony. Tangible objects are classified as real, demonstrative, or documentary evidence and handled in court as exhibits. In turn, these tangible objects normally require accompanying witness testimony either in the form of lay testimony or by an expert witness.

•Real Evidence

Real evidence is an item or object. Its existence or characteristics are considered relevant and material to an issue in a trial. It is a thing that was directly involved in some event in the case, such as a murder weapon, the personal effects of a victim or an artifact such as a cigarette or lighter belonging to a suspect. Real evidence must be relevant, material and competent before a judge will permit its use in a trial.⁸⁸ The process whereby a lawyer establishes these basic prerequisites (and any additional ones that may apply), is called laying a foundation. In most cases, the relevance and materiality of real

⁸⁵ Giannelli, Understanding Evidence, 8.

⁸⁶ *Id.* at 10. The states opting out of the FRE include California, Illinois, Massachusetts, and New York, which illustrates that while the FRE have been influential, there are robust alternatives and important dissenting voices.

⁸⁷ *Id.* at 10.

⁸⁸ *Id.* at Chap. 26.

evidence are obvious. A lawyer establishes the evidence's competence by showing through his/her witnesses (lay or expert) that the "matter" (be it testimony or an exhibit) really is what it is supposed to be.⁸⁹ Establishing that real or other evidence is what it purports to be is called authentication.⁹⁰ In criminal cases involving bite mark evidence, dental models of a suspect's dentition and those taken from a victim's body are examples of real evidence.

- Demonstrative Evidence

Evidence is considered "demonstrative" if it demonstrates or illustrates the testimony of a witness.⁹¹ It is admissible when it fairly and accurately reflects the witness's testimony and is otherwise unobjectionable. Photographic overlays of bite marks, diagrams of a crime scene as well as charts and graphs that illustrate profits and losses are examples of demonstrative evidence.⁹²

- Documentary Evidence

Evidence contained in or on documents can be a form of real evidence. For example, a contract offered to prove the terms it contains is both documentary and real evidence. When a party offers a document into evidence, the party must authenticate it the same way as any other real evidence, either by a witness who can identify the document or by witnesses who can establish a chain of custody for the document.⁹³ In bite mark cases, the dental forensic expert may use his/her written report to assist in a trial.

⁸⁹ Giannelli, Understanding Evidence, 361-370.

⁹⁰ Id. at Chap. 26.

⁹¹ Id. at 370.

⁹² Id at 361-370.

⁹³ Id. at Chap. 28.

The best evidence rule⁹⁴ states that when the contents of a written document are offered in evidence, the court will not accept a copy or other proof of the document's content in place of the original document unless an adequate explanation is offered for the absence of the original. The FRE permits the use of mechanically reproduced documents unless one of the parties has raised a genuine question about the accuracy of the original or can somehow show that the use of a duplicate would be unfair (e.g., only a fragment of report survives).⁹⁵ Also under the FRE, summaries or compilations of lengthy documents may be received into evidence as long as the other parties have made the originals available for examination.⁹⁶

- Witness Testimony

Evidence given in the form of testimony is the most basic type of evidence. Testimonial evidence consists of what a competent witness says in court.⁹⁷ Modern evidence law often austere characterizes testimony as assuming one of two forms: lay and expert testimony. Lay testimony is based on our common knowledge and experience; it is what we all know or are capable of knowing based on our perception. Expert testimony is, by definition, based on specialized knowledge.⁹⁸ The courts interpret competency quite liberally, which means that lay testimony is rarely excluded. The possibility that a witness is lying or mistaken is usually left to the trier of fact to

⁹⁴ Giannelli, Understanding Evidence , 403.

⁹⁵ Id at 409.

⁹⁶ Id at 403.

⁹⁷ Id at 2.

⁹⁸ Id at 348.

resolve as a matter of weight. This is the case of *Doyle v. State*⁹⁹, the first case in the U.S. to confront the admissibility of expert testimony on bite mark identification.

In 1954, the Texas Court of Criminal Appeals admitted bite mark evidence for the first time. The defendant, Doyle, was charged with burglary of a grocery store. Doyle allegedly stole two bottles of whiskey and 13 silver dollars. He also ate some food on the counter, including a large piece of cheese. Later that day, Doyle was arrested for public intoxication and was found to have 13 silver dollars on him. The police were unaware of the grocery store break-in at the time of Doyle's arrest. When they learned of the stolen whiskey and 13 silver dollars, however, Doyle became a suspect. Since a piece of cheese with teeth marks was found at the crime scene, Doyle was requested to bite into another piece of cheese while in jail. A firearms examiner photographed and made plaster impressions of both pieces of cheese. The local dentist made an impression of Doyle's teeth and with the piece of cheese, testified at trial that the bite marks were from the same set of teeth. The presiding judge wrote that there was no material distinction between this case involving the teeth marks and those cases recognizing foot and fingerprints by the courts. The court never stated the criteria used for admissibility of the bite mark evidence or the qualifications of the experts and Doyle never questioned the expertise of the firearms examiner to prepare models.¹⁰⁰ Rather, the issue placed before the appeals court surrounded Doyle's constitutional rights with regard to the collection of evidence: *Doyle*, then, also illustrates that bite mark analysis is necessarily intertwined with the constitutional constraints placed on the gathering and collection of evidence from the accused.

⁹⁹ *Doyle v. State*, 159 Tex. Crim.310, 263 S.W. 2d 779 (1954).

¹⁰⁰ Faigman, Modern Scientific Evidence, 386.

Constitutional Problems in Collection of Evidence

There are primarily two constitutional problems that can occur during collection of evidence in a bite mark case. When an attempt is made to obtain photographs and impressions of a bite mark or dental impression of a suspect's teeth, the suspect may raise two objections: (1) the government violated his right against self-incrimination in obtaining the dental evidence (Fifth Amendment); and (2) the search and seizure of dental evidence violated his right to be free from unreasonable searches and seizures (the Fourth Amendment).¹⁰¹

Fifth Amendment Interpretation and Scope of the Self-Incrimination Clause

The Fifth Amendment's right against self-incrimination permits individuals to refuse to answer questions or disclose information that could be used against them in a criminal prosecution. The purpose of this right is to inhibit the government from compelling a confession through force, coercion or deception. Confessions produced by these methods are deemed unreliable because they are often involuntary, unwitting or the result of the suspect's desire to avoid further browbeating.¹⁰² It is important to understand why the collection of such potentially incriminating dental evidence is itself exempt from scrutiny under the privilege against self-incrimination.

In criminal proceedings, the U.S. Supreme Court's decision in *Miranda v. Arizona*¹⁰³ established the rules under which the Self-Incrimination Clause applies to proceedings before trial. In *Miranda*, the Court held that any statements made by a defendant while in police custody will be inadmissible during prosecution unless the

¹⁰¹ Dinkel, "The Use of Bite Mark Evidence as an Investigative Aid," 543.

¹⁰² Wayne R. LaFave et al., Criminal Procedure, St. Paul, MN: West Publishing Company, 5th ed. (2009) Sec. 6.2.

¹⁰³ *Miranda v. Arizona*, 384 U.S. 436 (1966).

police first warn the defendants that they have the right: (1) to remain silent; (2) to consult an attorney before being questioned by the police and to have an attorney present during police questioning; (3) to have a court-appointed attorney if the defendant cannot afford to hire a private attorney; and (4) to be informed that any statements the individual makes can and will be used against him at trial.¹⁰⁴ The *Miranda* case acknowledged that these warnings were not expressly mentioned anywhere in the text of the federal Constitution. The Court, however, concluded that the warnings constituted an essential part of a judicially created buffer zone that is necessary to protect a suspect's rights. Thus, if a defendant confesses to a crime or makes an otherwise incriminating statement in response to police questioning, such statements will be generally excluded from trial unless the defendant first waived his Miranda rights.¹⁰⁵

The Fifth Amendment to the Constitution is limited to testimonial evidence, not the physical characteristics of evidence. Dental impressions are not testimonial evidence because testimonial evidence is from a suspect's mind and does not embrace physical characteristics.¹⁰⁶ When a bite mark is found on a victim, the dental forensic scientist is called upon to take dental impressions of alleged suspects. This involves the mixture of dental alginate and water to a desired consistency and placed in dental impression trays. The trays are then placed one at a time to each arch in the human mouth. The impression material quickly hardens, trays are removed, and the individual's dental arches are duplicated. Plaster material is then added to the dental impressions and dental models or casts are formed within 24 hours. This dental evidence is then evaluated in relationship

¹⁰⁴ *Id.* at 479.

¹⁰⁵ LaFave at Sec. 6.9.

¹⁰⁶ *Pennsylvania v. Muniz*, 496 U.S. 582 (1990).

to the bite mark(s). There are no reports of litigated cases challenging the constitutionality of compelling a suspect to submit to dental impressions. Again, dental impressions are solely physical evidence, not testimonial in nature.

Two cases illustrate confession law's preoccupation with testimonial evidence. In *Schmerber v. California*¹⁰⁷, the Supreme Court held that the Fifth Amendment privilege "protects an accused only from being compelled to testify against himself or otherwise provide the State with evidence of a testimonial or communicative nature." The Court further noted, "Both federal and state courts have usually held that it (the Fifth Amendment) offers no protection against compulsion to submit to fingerprinting, photographing or measurements...."¹⁰⁸

In the bite mark case of *People v. Milone*¹⁰⁹, the court observed that the defendant did not resist while the photographs and impressions of his teeth were being made, nor was he harmed or put in an uncomfortable position by police, who treated him courteously. The defendant had photographs and impressions made of his teeth in order to match them with bite marks found on the body of the victim, and thus, did not violate the defendant's Fifth Amendment right against self-incrimination. Dental impressions, similar to fingerprints or voice exemplars, are fixed characteristics of the body, and do not fall under the umbrella of the Fifth Amendment. The collection of physical evidence from a suspect implicates search and seizure doctrine, rules which are governed by the Fourth Amendment.

¹⁰⁷ *Schmerber v. California*, 384 U.S. 757 (1966).

¹⁰⁸ *Id.*

¹⁰⁹ *People v. Milone*, 43 Ill. App.3d 385, 2 Ill. Dec.63, 356 N.E. 2d 1350 (2d Dist. 1976).

The Fourth Amendment: Interpretation and Scope of Search and Seizure Principle

The Fourth Amendment to the U.S. Constitution states, “The right of people to be secure in their persons, houses, papers, and effects, against unreasonable searches and seizures, shall not be violated, and no Warrants shall issue, but upon probable cause, supported by Oath or affirmation, and particularly describing the place to be searched, and the persons or things to be seized.”¹¹⁰ This amendment requires a warrant for arrests and for searches of persons, homes, and other private places. It thereby places a neutral magistrate between the police and citizens.¹¹¹

Given the demands of dental forensic science to take a dental impression of a suspect’s mouth, first there may be a seizure of the person which brings the suspect under control of the police. And second, the taking of the bite impression from that person sufficiently amounts to a search to comply with the Fourth Amendment.¹¹² The Fourth Amendment sets forth the minimum amount of protection that both the state and federal government must provide against searches and seizures.¹¹³ Thus, law enforcement must have a search warrant or consent prior to taking dental impressions of suspects.

The Fourth Amendment has three components: (1) it establishes a privacy interest by recognizing the right of every citizen to be secure in their persons, houses, papers and effects¹¹⁴; (2) it protects this privacy interest by prohibiting searches and seizures that are not authorized by a warrant based on probable cause or that are

¹¹⁰ Fourth Amendment, U.S. Constitution.

¹¹¹ LaFave at 181.

¹¹² Paul C. Giannelli and Edward J. Imwinkelried, Bite Mark and Dental Identification, 3rd ed. (1999), 603.

¹¹³ LaFave at Sec. 3.4(a).

¹¹⁴ LaFave at Sec. 3.2.

otherwise unreasonable¹¹⁵; and (3) for searches requiring a warrant, it states that the warrant must describe with particularity the place to be searched, and the persons or things to be seized and be supported by oath or affirmation of the officer requesting the warrant.¹¹⁶

Not every search and seizure that is scrutinized in state and federal court raises a Fourth Amendment issue. The Fourth Amendment only protects against searches and seizures conducted by the government or pursuant to governmental direction. Surveillance and investigatory actions by private persons, such as private investigators, suspicious spouses or nosy neighbors, are not governed by the Fourth Amendment. Fourth Amendment concerns arise, however, when those same actions are taken by a law enforcement official or a dentist working in conjunction with law enforcement.¹¹⁷

The Fourth Amendment does not apply even against governmental action unless defendants first establish that they have a reasonable expectation of privacy in the place to be searched or the thing to be seized. The Supreme Court has explained that what "a person knowingly exposes to the public, even in his own home or office, is not a subject of Fourth Amendment protection . . ." but what he seeks to preserve as private, even in an area accessible to the public, may be constitutionally protected.¹¹⁸ Yet the question remains: What part of an individual is private?

In the mid-1960s, the Supreme Court ruled in *Katz v. United States*¹¹⁹ that the Fourth Amendment protects people, not property. Prior to *Katz*, the Court rigidly

¹¹⁵ LaFave at Sec. 3.4.

¹¹⁶ *Id.*

¹¹⁷ *Id.*

¹¹⁸ *Katz v. United States*, 389 U.S. 347, 88 S. Ct. 507, 19 L.Ed.2d 576 (1967).

¹¹⁹ *Id.*

interpreted the Fourth Amendment as regulating property. Unless the police violated someone's property rights, as in trespassing, there was no Fourth Amendment violation. In *Katz*, the Supreme Court announced a twofold requirement to determine whether a search is constitutional under the Fourth Amendment. First, the individual being searched must have an actual, subjective expectation of privacy and, second, the expectation must be one that society is prepared to recognize as reasonable.¹²⁰ The *Katz* case instituted profound change.

In *Katz*, the defendant was convicted of transmitting wagering information by telephone across state lines in violation of a federal statute. The evidence used to convict him was obtained by an electronic listening and recording device the FBI attached to the outside of the public telephone booth from which the defendant had placed his calls. The Supreme Court found that the eavesdropping constituted a search. The Court held that the Fourth Amendment protected the defendant from the warrantless eavesdropping because he justifiably relied upon the privacy of the telephone booth; however, the Court added to this standard by instructing that a reasonable person must also have expected privacy. *Katz* did not meet this test because reasonable people would not have an expectation of privacy in a public phone booth. Thus, the Court determined that an inspection of what is voluntarily exposed to the public (i.e., a conversation on a public phone) is not a violation of the Fourth Amendment. Yet, the telephone conversation was protected because *Katz* did not expect a third party to be listening to his conversation. The public phone booth where *Katz* was standing was not protected, and failure to obtain

¹²⁰ *Id.* at 361. (Harlan J., concurring).

a search warrant violated Katz's expectation of privacy.¹²¹ The *Katz* case defined a search as a police intrusion into one's reasonable expectation of privacy; any search or seizure is governed by the Fourth Amendment, which requires a search warrant or some exception to the warrant requirement.

The Supreme Court has said that individuals do not possess an expectation of privacy in their personal characteristics.¹²² Thus, the police may require individuals to give hair, blood, DNA and fingerprint samples without complying in accordance with the Fourth Amendment's requirements.¹²³ In *Schmerber*, the defendant was involved in an accident and subsequently convicted of driving under the influence of alcohol. While at the hospital, the police ordered a blood sample taken from the defendant to determine his blood-alcohol level. The report of his blood-alcohol level was admitted at trial over the defendant's objection that the test violated his Fourth Amendment rights. The Supreme Court found probable cause existed to take the blood test because the police officer noticed symptoms of drunkenness, and the blood test was likely to reveal the level of intoxication. The extraction of the defendant's blood samples was reasonable because the search was minimally intrusive and because the procedure involved virtually no risk of trauma or pain.¹²⁴ In addition, a blood test is recognized as a minimal search with little invasion of the individual's privacy interest even though it requires penetration under the skin. *Schmerber* recognized society's judgment that blood tests do not constitute an unduly extensive imposition on an individual's personal privacy and bodily

¹²¹ *Id.*

¹²² *United States v. Dionisio*, 410 U.S. 1 (1973).

¹²³ *LaFave* at 210-211.

¹²⁴ *Schmerber* at 771.

integrity.¹²⁵ An example of this relating to forensic dentistry is demonstrated in *People v. Smith*.¹²⁶

In *People v. Smith*, the victim was mutilated by apparent bite marks. The court recognized that dental evidence had gained general scientific acceptance so as to justify the uncontradicted testimony of the forensic odontologist that the defendant had administered bite marks to the murdered victim. Dental casts of the accused were needed to confirm that opinion. This was sufficient to establish probable cause to justify the order to require dental impressions and photographs of the defendant's lower teeth and bite for the purposes of prosecution for first-degree murder. The court further held that the prosecution sufficiently justified its request in light of the fact that the procedures for dental impressions and photographing of the teeth were painless, without risk, could be completed in a matter of minutes and could be important as a means of possible exclusion of the defendant.¹²⁷ While these procedures were relatively unintrusive to the defendant, they constituted his right of reasonable privacy and were considered search and seizures under the Fourth Amendment.

In addition to the Fourth Amendment, the due process clause protects against overly invasive procedures. In *Rochin v. California*,¹²⁸ the police went into the defendant's home with suspicion that the defendant may have been selling narcotics. The police took the defendant to the hospital to have his stomach pumped in order to retrieve two capsules they saw him swallow. The Supreme Court found that pumping the defendant's stomach was so intrusive that it "shocked the conscience," "offended a sense

¹²⁵ *Id.* at 771, n.13.

¹²⁶ *People v. Smith*, 110 Misc 2d 118, 443 N.Y.S. 2d 551 (1981).

¹²⁷ *Id.*

¹²⁸ *Rochin v. California*, 342 U.S. 165, 166 (1952).

of justice" and ran "counter to the decencies of civilized conduct."¹²⁹ Consequently, the Court ruled that without a search warrant, this type of search was unconstitutional.¹³⁰

Under the Fourth Amendment, the intrusiveness of dental photographs, bite impressions, and dental casts are not a violation of a suspect's rights in the same way that the courts have forbidden stomach pumping and surgery to collect evidence. Yet the Court has had to decide on a case-by-case basis as in *Winston v. Lee*.¹³¹ Neither probable cause nor the need to gather crucial evidence in *Winston* would allowed for minimally-invasive surgery to occur because the personal intrusion was ultimately considered so extreme.

In that case, the court defined a limit regarding the collection of evidence. One evening, Mr. Watkinson was closing up his shop for the night when he observed someone [Mr. Lee] armed with a gun coming toward him from across the street. Watkinson was also armed and when he drew his gun, Lee told him to freeze. Watkinson then fired at Lee, who returned his fire. Watkinson was hit in the legs, while Lee was wounded in his left side and ran from the scene. Watkinson was taken to the emergency room. Approximately 20 minutes later, police officers found Lee suffering from a wound to his left chest area and took him to the same hospital where Watkinson was being treated. In the hospital, Watkinson identified Lee as the man who shot him.¹³²

After an investigation, the police decided Lee's story of having been himself the victim of a robbery was untrue and charged him with attempted robbery, malicious

¹²⁹ *Id.* at 166.

¹³⁰ *Id.* at 174.

¹³¹ *Winston v. Lee*, 470 U.S. 753, 757 (1985).

¹³² *Id.*

wounding and two counts of using a firearm in the commission of a felony. The government moved in state court for an order directing Lee to undergo surgery to remove an object thought to be a bullet lodged under his left collarbone. This vital piece of evidence was needed to trace the victim's gun and thereby identify the defendant in the case.

The court conducted several evidentiary hearings on the motion. Medical experts testified about the length of the surgical procedure (about 45 minutes) and the chances of damages and death (3-4 percent chance of temporary nerve damage, a 1 percent chance of permanent nerve damage and a one-tenth of 1 percent chance of death). Other experts testified that the bullet was not back inside close to the nerves and arteries rather, the bullet was located just beneath the skin.¹³³ The court found that the reasonableness of surgical intrusions beneath the skin depends on a case-by-case approach, in which the individual's interests in privacy and security are weighed against society's interests in conducting the procedure to obtain evidence for fairly determining guilt or innocence.¹³⁴

In a given case, the question whether the community's need for evidence outweighs the substantial privacy interests at stake is a delicate one.¹³⁵ There was conflicting testimony concerning the nature and scope of the operation in regards to surgical time, risks of infection, and use of general anesthesia. The court noted the intrusion to take control of Lee's body, to "drug this citizen-not yet convicted of a criminal offense-with narcotics and barbiturates into a state of unconsciousness,"¹³⁶ and then search beneath his skin for evidence of crime. Although the bullet in Lee could be

¹³³ *Id.*

¹³⁴ Lee, 470 U.S. at 754-755.

¹³⁵ Lee, 470 U.S. at 761.

¹³⁶ 717 F. 2d, at 901.

useful to the trial, the prosecution failed to demonstrate a reasonable search for evidence of this crime by means of the contemplated surgery under the Fourth Amendment.¹³⁷

Under the Fourth Amendment, the key in dental forensic cases is whether a suspect has a reasonable expectation of privacy in his or her dentition. In *Schmerber*, the court stated:

“The overriding function of the Fourth Amendment is to protect personal privacy and dignity against unwarranted intrusion by the State. The values protected by the Fourth Amendment thus substantially overlap those which the Fifth Amendment helps protect. The Fourth Amendment’s proper function is to constrain, not against all intrusions as such, but against intrusions which are not justified in the circumstances or which are made in an improper manner.”¹³⁸

Unless law enforcement has consent, the Fourth Amendment requires a search warrant prior to seeking dental evidence of a suspect. Added to the legal concepts of evidence and the rulings on the Fourth and Fifth Amendment rights are the issue of validating the scientific evidence. Even if the dental forensic evidence is gathered in a lawful manner, the rules of evidence will regulate its use at trial.

Validation of Scientific Evidence: The Power of Expert Testimony

A jury comprised of ordinary, intelligent laypeople does not always need an expert’s testimony to understand the scientific evidence presented at trial. This is referred to as commonplace information (e.g., the sun rises in the east). Yet, even though scientific evidence may be commonplace, there is a need for determining the proper boundaries of what constitutes expert testimony. The courts consider an expert to be a person whose knowledge, training and experience creates an understanding of facts that

¹³⁷ Lee, 470 U.S. at 767.

¹³⁸ *Schmerber v. California*, 384 U.S. at 757.

are outside the abilities of the average individual.¹³⁹ At the other end of the spectrum lies the boundary between good science and unreliable science.¹⁴⁰ However, it is the testimony of the expert before a jury that may affect the validation of the science and possibly the outcome of a trial.

No rational juror takes issue with accepting fingerprints as physical evidence in criminal investigations, yet how did this common belief in the individuality of fingerprints come to pass? In 1911, the system of fingerprint identification was ruled as admissible evidence in court because its method of identification was general and common.¹⁴¹ Rarely are crime lab analysts (experts in their field of fingerprint analysis) called into court to explain their scientific methodology and expertise. Often police officers testify as experts on various types of criminal activities such as counterfeiting, organized crime and drug trafficking.¹⁴² Yet, many jurors, as well as lawyers, apparently assume these witnesses constitute credible expert authority.

When the Federal Rule of Evidence 702 (Rule 702) was originally drafted in 1975, it opened the way for expert testimony to assist jurors in deciding cases. Before this rule went into effect, common law limited expert testimony to only those situations when it was necessary to help juries. Now the dominant standard in the United States, Rule 702 embodied a more flexible general relevance test for admissibility of opinion testimony by expert witnesses. Its standard of helpfulness was more generous and erred

¹³⁹ Fed. R. Evidence. 702. See also C. Michael Bowers, Forensic Dental Evidence, (2004) 181.

¹⁴⁰ Giannelli, Understanding Evidence, 311.

¹⁴¹ Larry A. Barry, "Bite Mark Evidence Collection in the United States," Bulletin of the History of Dentistry 42:1 (March 1994): 21-26.

¹⁴² Giannelli, Understanding Evidence, 311.

on the side of assisting juries with getting the facts right. According to Rule 702, the trial judge decides whether a subject is a proper one for expert testimony.¹⁴³

The reliability of evidence derived from scientific theory depends on three factors, at least as understood under present Rule 702: (1) the validity of the underlying theory, (2) the validity of the technique applying that theory, and (3) the proper application of the technique on a particular occasion.¹⁴⁴ For example, a layperson could accept the theory that a human bite mark is unique to an individual's dentition and that dental impressions taken of a suspect's mouth display uniqueness; however, the question might still remain whether the methodology to determine a particular bite mark on a victim's body displays the same uniqueness found in the dental impressions of a suspect. The method of proof for bite marks evidence involves the visual presentation and testimony from a qualified dental forensic scientist and can vary depending upon the scope of the methodology of the measurements analyzed for comparison.

The courts have been skeptical of scientists' claims of the virtual infallibility of scientific techniques and feared that jurors will be misled and ineffective in their fact-finding duties.¹⁴⁵ For this reason, many courts require an extraordinary foundation of scientific evidence. The jurisdictions are divided among three different approaches related to the validity of scientific evidence: (1) the *Frye* "general acceptance" test, (2) McCormick's relevancy approach, and (3) the federal reliability standard contained in present Rule 702. Although the Rule 702 standard is the law in federal court and in a

¹⁴³ *Id.* at 311.

¹⁴⁴ *Id.*

¹⁴⁵ Edward J. Imwinkelried, Evidentiary Foundation, Newark, NJ: LexisNexis, 6th ed. (2005).

majority of the states, the *Frye* standard remains the law in a significant minority of jurisdictions while the relevancy standard commands little loyalty at present.¹⁴⁶ To understand these three approaches, it is important to keep in mind that reliability refers to consistent outcomes and validity refers to the accuracy of measurements. While the law fails to understand or appreciate scientific reasoning, dental forensic scientists take great care and time to distinguish between the concepts of reliability and validity.

General Acceptance Test: The Frye Test

Courts have struggled with how to determine the reliability of expert testimony for the better part of the 20th century.¹⁴⁷ In 1923, the Circuit Court of Appeals for the District of Columbia developed an early and influential test for assessing expert testimony in *Frye v. United States*.¹⁴⁸ The *Frye* court was confronted with a defendant who sought admissibility of the results of a systolic blood pressure deception test (precursor to the polygraph machine) in order to prove the defendant was telling the truth. The test was based on the theory that telling the truth is spontaneous and without conscious effort, while lying is a conscious effort reflected by a change in blood pressure.¹⁴⁹ The court held that the polygraph had “not yet gained such standing and scientific recognition among physiological and psychological authorities.”¹⁵⁰

¹⁴⁶ Id. at 163. For an overview of these three standards of admissibility, see Giannelli, *supra*, § 24.04.

¹⁴⁷ Ira. H. Leesfield and Mark A Sylvester, “Admissibility of Expert Testimony: What’s Next?” http://expertpages.com/news/admissibility_testimony.htm (Last visited March 2010).

¹⁴⁸ *Frye v. United States*, 293 F. 1013, 1014 (D.C. Cir. 1923).

¹⁴⁹ P. Zarowski, “Bite Mark Evidence: Its Worth in the Eyes of the Expert,” *J Law Ethics Dent* 1:47 (1988).

¹⁵⁰ *Frye v. United States*, 293 F. at 1014.

When scientific evidence is at issue, the *Frye* rule allows the judge to defer to scientific expertise on the basis of whether or not it has gained general acceptance in the relevant field. The court's gatekeeper role in this case was conservative, thus helping to keep "pseudoscience"¹⁵¹ out of the courtroom. It was believed that the general acceptance concept from a scientific community would scrutinize all its applicable research with rigorous tests and techniques before giving a stamp of approval. This decision was the birth of what ultimately became known as the general acceptance test or the *Frye* test. While ignored initially by other courts, the *Frye* test would, by the end of the 1980s, become the majority test for the admissibility of scientific evidence such as voiceprints, gunshot residue tests, bite mark comparisons, truth serum, hypnosis, blood and hair analyses, and DNA profiling.¹⁵²

Specifically in *Frye*, the Circuit Court of Appeals held that for scientific evidence to be admissible, the party offering it must establish that the expert testimony and the techniques used are generally accepted as reliable in the scientific community. The Court maintained:

Just when a scientific principle or discovery crosses the line between the experimental and demonstrable stages is difficult to define. Somewhere in this twilight zone the evidential force of the principle must be recognized, and while courts will go a long way in admitting expert testimony deduced from a well-recognized scientific principle or discovery, the thing from which the deduction is made must be sufficiently established to have gained general acceptance in the particular field in which it belongs.¹⁵³

¹⁵¹ Pseudoscience is defined as a system of theories, assumptions, and methods erroneously regarded as scientific. Webster's New Collegiate Dictionary, 930.

¹⁵² Giannelli, *Understanding Evidence*, 301.

¹⁵³ *Frye*, 293 F.1014.

The first application of the *Frye* standard test in a bite mark case was in *People v. Marx*.¹⁵⁴ The case involved a brutal murder of an elderly woman who had an elliptical laceration on her nose. The laceration was judged to be a human bite and impressions were made of the wound for comparison with a dental cast of the defendant's teeth. According to a legal expert, three dental forensic scientists testified that the dentition at issue was extremely unusual, the bite mark was exceptionally well-defined, and that the defendant's dentition matched the bite wound. On appeal, the defendant argued that under California law, the experts' opinions on bite mark identification were not generally accepted in the field of forensic dentistry.

The *Marx* court concluded that the dental experts applied scientifically and professionally established techniques: x-rays, models, microscopy, photography that was well within the capability of those techniques; all of the results from these techniques were clearly visible for the jurors to view, assess and verify on their own during the court proceedings. Thus, the "court did not have to sacrifice its independence and common sense in evaluating" the dental forensic evidence.¹⁵⁵

One year later in *People v. Milone*¹⁵⁶ the Illinois court found that the victim was murdered with a shopping cart handle, which the defendant carried as his personal weapon. Other evidence which linked Milone to the crime included: (1) the defendant was absent from his place of employment for nearly one hour on the evening of the murder, (2) the defendant lied about his whereabouts to detectives investigating the

¹⁵⁴ *People v. Marx*, 54 Cal. App. 3d 100, 126 Cal. Rptr. 350, 77 A.L.R. 3d 1108 (2d Dist. 1975).

¹⁵⁵ Giannelli, *Understanding Evidence*, 301.

¹⁵⁶ *People v. Milone*, 43 Ill. App. 3d 385, 2 Ill. Dec. 63, 356 N.E. 2d 1350 (2d Dist. 1976).

murder, and (3) the defendant's automobile matched a description of the car seen near the scene of the crime. This was sufficient to sustain the defendant's conviction.¹⁵⁷ In addition, the concept of identification by matching a defendant's dentition to a bite mark on the victim's thigh was a logical extension of the accepted principle that each person's dentition is unique. In *Milone*, there were three expert witnesses for the prosecution and four for the defense that disagreed sharply on the question of the validity and utility of bite mark identification. This illustrates the limits of *Frye* where by the verdict rendered favored the side that produced the most experts.

The general acceptance/*Frye* test was plagued with problems from the outset. First and foremost was the lack of objectivity in defining the terms "relevant scientific community" and "general acceptance." The terms lacked objective standards or empirical testing and were susceptible to subjective interpretation by the courts, thus allowing trial judges to control the admissibility of expert testimony based on what they personally believed was credible and reliable.¹⁵⁸ The complaint most commonly voiced, however, was that the test was too rigid and inflexible, resulting in the exclusion of evidence that should have been admitted as reliable and relevant.¹⁵⁹ Perhaps this is why some courts abandoned this approach and chose instead to use McCormick's Relevancy Standard.

McCormick's Relevancy Standard

The common law had limited expert testimony to instances where it was necessary as a matter of law; however, others strenuously argued for a more liberal

¹⁵⁷ *Id.*

¹⁵⁸ Paul C. Giannelli, "The Admissibility of Novel Scientific Evidence: *Frye* v. United States, Half-Century Later," 80 *Colum. L. Rev.* 1197, 1250 (1980).

¹⁵⁹ Leesfield and Sylvester, "Admissibility of Expert Testimony: What's Next?"

approach favoring expert testimony in cases where it may help the jury better understand the case. Professor Charles T. McCormick, the author of a 1954 treatise still heavily used by the courts, advocated for a relevancy standard that placed great faith in the adversary trial and the abilities of lay jurors. McCormick explains the relevancy standard as follows:

General scientific acceptance” is a proper condition upon the court’s taking judicial notice of scientific facts, but not a criterion for the admissibility of scientific evidence. Any relevant conclusions which are supported by a qualified expert witness should be received unless there are other reasons for exclusion.¹⁶⁰

Today the relevancy test holds sway only in a small number of jurisdictions.¹⁶¹

The 1986 case of *State v. Stinson*¹⁶² illustrates the concepts of the McCormick relevancy standard. This case involved a 62-year-old woman who was found beaten to death in Stinson’s backyard near her home and no eyewitnesses willing to testify. A dental forensic expert was called to examine and document multiple-patterned injuries suspected of being human bite marks. A total of eight bite marks were photographed, sketched, impressed, dissected and preserved for additional testing. A dental profile was developed using 72 individual tooth marks with distinct characteristics, including missing upper teeth and ragged, irregular lower teeth. A sketch was made to demonstrate this profile for homicide investigators, who later recognized missing upper teeth in three out of four suspects they questioned. With only the bite marks to link the suspect to the crime, all four suspects submitted voluntarily to a dental examination, as well as Robert Lee Stinson’s fraternal twin brother, who was not a suspect. Two forensic odontologists

¹⁶⁰ McCormick’s Evidence, (1954) 363-364.

¹⁶¹ Giannelli, supra, § 24.04[B] for a discussion and critique of the relevancy standard.

¹⁶² *State v. Stinson*, 134 Wis.2d 224, 397 N.W. 2d. 136 (Ct. App. 1986).

retained by the prosecution opined that the bite wounds were completely consistent with Robert Lee's dentition. The other individuals, including Stinson's brother, were excluded.¹⁶³

A jury convicted Robert Lee Stinson of first-degree murder because of the bite mark evidence linking him to the victim. The Stinson conviction was largely based on the testimony of two experts in the field of forensic odontology who testified on the subject of bite mark identification. Both experts for the prosecution concluded with a reasonable degree of scientific certainty that the bite marks on the victim were inflicted at or near the time of death and that Stinson was the only person who could have inflicted the wounds.¹⁶⁴ McCormick's definition of relevancy declared that "[a]ny relevant conclusions which are supported by a qualified expert witness should be received" into evidence.¹⁶⁵ However, no defense witnesses were called to testify and the only expert report from the defense was given to the court in a sealed envelope.¹⁶⁶

Stinson appealed on several grounds: (1) the bite mark evidence was improperly admitted; (2) there was insufficient evidence to support a verdict of first-degree murder; (3) the trial court erred by improperly restricting defense counsel's reference to an article written by one of the State's experts; and (4) the trial court denied Stinson's request to discharge his defense counsel and substitute another on the second day of the jury trial. The court of appeals held the expert testimony on bite mark identification was admissible based on the relevancy test. The State's experts were qualified, the testimony was

¹⁶³ State v. Stinson, 397 Wis.2d at 230.

¹⁶⁴ State v. Stinson, 397 Wis.2d at 238.

¹⁶⁵ McCormick, supra note 99, 171, at 363-364.

¹⁶⁶ In 2009 the judgment of conviction was later reopened and dismissed based on the work of the Wisconsin Innocence Project: R.L. Stinson, Evaluation of Bitemark Evidence, February 13, 2008.

relevant, and it assisted the jury in determining if Stinson was the killer. The court also held that there was sufficient evidence to support the verdict of first-degree murder since the evidence enabled the jury to see comparisons being made by the dental experts and to determine that Stinson's teeth did in fact match a total of 14 upper- and lower-jaw impressions made from the bite marks found on the victim's body. The dental experts could identify 75 individual marks in various combinations of between 5 and 11 teeth that matched Stinson's tooth formations.¹⁶⁷

The McCormick relevancy standard is not without its critics, however. One viewpoint contends that "the major flaw in the relevancy analysis ... is its failure to recognize the distinctive problems of scientific evidence.... The judge frequently is forced to defer to an expert, thereby permitting admissibility based on the views of a single individual in some cases."¹⁶⁸ In the *Stinson* case, the defense lawyers offered no expert testimony to contest the prosecution's bite mark evidence.¹⁶⁹ Thus, the *Stinson* jury had no reason to reject the bite mark evidence presented by the prosecution's experts as that of Robert Stinson, the defendant. In most adversarial trials, jurors should be able to evaluate the reliability of the conflicting expert testimony.

Federal Rule of Evidence 702

Three important cases in the 1990s, *Daubert v. Merrell Dow Pharmaceuticals*¹⁷⁰, *General Electric Co. v. Joiner*¹⁷¹, and *Kumho Tire Ltd. v. Carmichael*¹⁷² laid the

¹⁶⁷ *State v. Stinson*, 397 Wis. at 239-240.

¹⁶⁸ Giannelli, Paul C. "The Admissibility of Novel Scientific Evidence: *Frye v. United States*, Half-Century Later," 80 *Colum. L. Rev.* 1197, 1250 (1980): 302.

¹⁶⁹ *State v. Stinson*, 397 Wis. at 242.

¹⁷⁰ *Daubert v. Merrell Dow Pharmaceuticals*, 509 U.S. 579 (1993).

¹⁷¹ *General Electric Co. v. Joiner*, 522 U.S. 136, 146 (1997).

¹⁷² *Kumho Tire Ltd. v. Carmichael*, 119 S. Ct. 1167, 1176 (1999).

foundation for the revision of Federal Rule 702, which comprises the trilogy of expert witness law in the federal courts. As originally drafted, Federal Rule of Evidence 702 stated:

If scientific, technical or other specialized knowledge will assist the trier of fact to understand the evidence or to determine a fact in issue, a witness qualified as an expert by knowledge, skill, experience, training or education may testify hereto in the form of an opinion or otherwise.

Reliability tests based on expert testimony are not only followed in all federal and military courts today, but in most states as well. It is important to understand these three cases and the rationale that have sustained the reliability standard.

- The Daubert Reliability Standard

Jason Daubert of San Diego, California, was born with only two fingers on his right hand and without a lower bone on his right arm. As birth defects go, limb deformities such as Jason's are relatively common, afflicting about 1 in 2,000 American infants born each year. While pregnant, Jason's mother took Bendectin, a drug for morning sickness that ultimately was driven off the market by the pressure of lawsuits asserting that the medication caused birth defects. Before manufacturer Merrell Dow Pharmaceuticals, Inc., dropped Bendectin, about 33 million women used it because scientific studies overwhelmingly concluded that it was safe. All but a handful of suits against the pharmaceutical company had been dismissed, except a suit filed in a California federal court by lawyers for the Daubert family.

In *Daubert*, the plaintiffs' contended that Bendectin likely caused the birth defects. The trial court, however, determined that the evidence presented by the plaintiffs' experts did not meet the general acceptance standard for admission because they could not prove causation. Without any admissible evidence of causation before it,

the district court granted summary judgment in favor of the defendant. The Ninth Circuit affirmed this decision.

When the *Daubert* case reached the U.S. Supreme Court, the Court stated that evidence based on novel scientific knowledge should be admissible only after it has been established that the evidence is reliable and scientifically valid.¹⁷³ Specifically, the Court stated that "the *Frye* test was superseded by the adoption of the Federal Rule of Evidence."¹⁷⁴ Moreover, the Court said that the rigid general acceptance requirement of *Frye* was "at odds with the 'liberal thrust' of the federal rules and their 'general approach of relaxing the traditional barriers to opinion testimony.'"¹⁷⁵ Proponents of the general acceptance test argued that the *Daubert* ruling would open the floodgates to unfounded and unreliable evidence. They feared that juries would be misled and confused by evidence that was not credible and generally accepted in the scientific community. The Court addressed these concerns by levying the task of managing the admission of evidence on the trial judge.

Specifically, the Supreme Court cast upon the trial judges the duty to act as gatekeepers charged with preventing "junk science"¹⁷⁶ from entering the courtroom. "Junk science is matched by what might be called liability science, a speculative theory that expects lawyers, judges, and juries to search for causes at the far fringes of science and beyond."¹⁷⁷ In order to assist judges in fulfilling their roles, *Daubert* articulated criteria for the admissibility of scientific evidence:

¹⁷³ *Daubert v. Merrell Dow Pharmaceuticals*, 509 U.S. 579 (1993).

¹⁷⁴ *Daubert* 509 U.S. at 587.

¹⁷⁵ *Daubert* citing *Beech Aircraft Corp. v. Rainey*, 488 U.S. 153, 169 (1988).

¹⁷⁶ Peter W. Huber, *Galileo's Revenge*, Baser Books, 1991.

¹⁷⁷ *Id.* at 3.

- Whether the scientific theory can be (and has been) tested;
- Whether the scientific theory or technique has been subjected to peer review and published;
- Whether the potential rate of error is known;
- Whether the existence and maintenance of standards controlled the technique's operation; and
- Whether it has been generally accepted.¹⁷⁸

Some lower courts applied all four criteria, while others have limited the holding only to scientific expert testimony. Despite the Court's attempt to liberalize the admission of expert testimony, the ruling arguably resulted in more confusion.¹⁷⁹

Rather, *Daubert* "has created a more stringent test for expert evidence admissibility."¹⁸⁰

•The *Joiner* Case

The first instance to employ an “assist-the-jury” standard for expert testimony that literally attempted to assist the jury came in *General Electric Co. v. Joiner*¹⁸¹ in 1997. The plaintiff's experts testified that Robert Joiner's lung cancer had been caused by polychlorinated biphenyls (PCBs) that were present in his workplace. In *Joiner*, the Supreme Court amplified its *Daubert* holding. The Court stated that in reviewing the decision of a trial court to either admit or deny admission of certain expert testimony—whether on the issue of the judge's determination of reliability/unreliability or on the ultimate conclusion reached by an expert—a court of appeals must use an abuse-of-discretion standard.¹⁸² Chief Justice Rehnquist, writing for the majority, noted that a trial judge need not accept expert testimony which is connected to existing data only by

¹⁷⁸ *Daubert* at 593-594. See also Faigman, Modern Scientific Evidence, 26.

¹⁷⁹ Leesfield and Sylvester, “Admissibility of Expert Testimony: What’s Next?”

¹⁸⁰ Michael H. Graham, “The Expert Witness Predicament: Determining ‘Reliable’ Under the Gatekeeping Test of *Daubert*, *Kumho*, and Proposed Amended Rule 702 of the Federal Rules of Evidence,”

U. MIAMI LAW REV. 54 (2000): 317-321.

¹⁸¹ *General Electric Company v. Joiner*, 522 U.S. 136, 146 (1997).

¹⁸² *Id.*

the *ipse dixit*¹⁸³ of the expert. A court may conclude that there is simply too great an analytical gap between the data and the opinion proffered.”¹⁸⁴ Justice Breyer, writing a concurring opinion, urged judges to seek assistance from the scientific community and to use court-appointed experts to strengthen their ability to understand scientific and technical evidence.¹⁸⁵

•*Kumho Tire*

In *Kumho Tire Co. v. Carmichael*¹⁸⁶, the Supreme Court held that the *Daubert* factors may apply to the opinion testimony of non-scientist expert witnesses. The expert in this case was an engineer with a master’s degree and ten years experience in the tire industry.¹⁸⁷ The *Kumho Tire* case was a diversity action suit against the maker and distributor of an automobile tire. The tire had blown out which caused the minivan on which it was mounted to turn over. In the accident, one passenger died and others were injured. The plaintiffs sought to make their case through the testimony of a tire failure analyst, who wanted to testify that a defect in the tire's design or manufacture caused the blowout. The expert's opinions were primarily based on his technical skill and extensive experience in the field rather than scientific principles.¹⁸⁸ The defendants sought to

¹⁸³ *Ipse dixit* is an unproved assertion.

¹⁸⁴ Jerome P. Kassirer and Joe S. Cecil, “Inconsistency in Evidentiary Standards for Medical Testimony,” *JAMA* 288:11 Reprinted (September 18, 2002): 1383. “The courts struggle to find standards to review medical decisions and often provide inconsistent legal judgments.”
medical expert testimony against the standards of medical practice.

¹⁸⁵ *Id.*

¹⁸⁶ *Kumho Tire Ltd. v. Carmichael*, 119 S. Ct. 1167, 1176 (1999).

¹⁸⁷ Giannelli, *Understanding Evidence*, 319.

¹⁸⁸ Leesfield and Sylvester, “Admissibility of Expert Testimony: What’s Next?”

exclude the expert's evidence on the basis that the methodology did not satisfy the requirements of the Federal Rule of Evidence 702.¹⁸⁹

The district court, applying the *Daubert* factors, agreed with defendants and granted the motion. The case ultimately reached the U.S. Supreme Court on the issue of whether *Daubert* factors applied only to expert evidence that was based on scientific knowledge. Applying the *Daubert* factors to the evidence, the trial court ruled that the testimony was inadmissible. The Eleventh Circuit reversed, holding that "the Supreme Court in *Daubert* explicitly limited its holding to cover only scientific principles" rather than "skill- or experience-based observation."¹⁹⁰

According to the Court, *Daubert* makes it clear that the list of factors for determining admissibility does not constitute a definitive checklist or test. Rather, the criteria were "meant to be helpful, not definitive."¹⁹¹ Significantly, *Kumho Tire* granted trial courts broad discretion in determining the reliability of expert testimony and built on the Court's earlier decision in *Joiner*.¹⁹² *Kumho Tire* expects courts to identify the nature of the particular problem that an expert is being asked to solve, and then to assess whether the available data support a conclusion that the necessary expertise exists to offer a dependable opinion on that problem.¹⁹³

¹⁸⁹ Giannelli, *Understanding Evidence*, 319-320.

¹⁹⁰ *Carmichael v. Samyang Tire Inc.*, 131 F. 3d 1433,1435. (S.D. Ala. 1996).

¹⁹¹ *Kuhmo Tire Co.*, 526 U.S. 137, 150.

¹⁹² 522 U.S. 136.

¹⁹³ Faigman, *Science in the Law*, 42-43.

•*The Seachange: Current Rule 702*

In light of the Court's trilogy in *Daubert-Joiner-Kumho Tire*, Federal Rule 702 was amended to reflect explicitly the adoption of the reliability standard in 2000. The revised version of Federal Rule 702 states:

If scientific, technical or other specialized knowledge will assist the trier of fact to understand the evidence or to determine a fact in issue, a witness qualified as an expert by knowledge, skill, experience, training, or education may testify thereto in the form of an opinion or otherwise if: (1) the testimony is based upon sufficient facts or data, (2) the testimony is the product of reliable principles and methods, and (3) the witness has applied the principles and methods reliably to the facts of the case.¹⁹⁴

The current rule requires that the testimony must be the product of reliable principles and methods that are reliably applied to the facts of the case.¹⁹⁵ With scientific knowledge, principles and methods should remain relevant when applied to the testimony based on technical or other specialized knowledge.¹⁹⁶ Nothing in this current rule is intended to suggest that experience alone-or experience in conjunction with other knowledge, skill, training or education- may not provide a sufficient foundation for expert testimony.¹⁹⁷ Consistent with *Kumho Tire*, amended Rule 702 provides that any type of expert testimony is subject to its reliability requirements. The current rule also acknowledges that the criteria espoused by *Daubert* are neither exhaustive nor exclusive.¹⁹⁸

¹⁹⁴ Fed. R. Evid. 702 advisory committee's note (2000).

¹⁹⁵ *Id.*

¹⁹⁶ *Id.*

¹⁹⁷ *Id.*

¹⁹⁸ Leesfield and Sylvester, "Admissibility of Expert Testimony: What's Next?"

There are potential problems with the current rule to Rule 702 despite the salutary attempt to clarify the doctrine.¹⁹⁹ The lack of an adequate definition of reliable scientific evidence leaves the determination to the trial judge, assuming that the trial judge has adequate knowledge to make this determination. In addition, the current rule fails to provide objective guidance for determining the reliability of expert testimony. As a result, it appears unlikely that the current rule will cure the unequal treatment of expert testimony by the trial courts.²⁰⁰ Courts both before and after *Daubert* have found a plethora of factors pertinent in determining whether expert testimony is sufficiently reliable to be considered by the trier of fact. Possible factors include:

- Whether experts are proposing to testify about matters growing naturally and directly out of research they have conducted independent of the litigation, or whether they have developed their opinions expressly for purposes of testifying.²⁰¹
- Whether the expert has unjustifiably extrapolated from an accepted premise to an unfounded conclusion. In some cases, a trial court may conclude that there is simply too great an analytical gap between the data and the opinion proffered.²⁰²
- Whether the expert has adequately accounted for obvious alternative explanations or causes.
- Whether the expert is being as careful as he would be in his regular professional work outside his paid litigation consulting.²⁰³ *Daubert* requires the trial court to assure itself that the expert employs in the courtroom the same level of intellectual rigor that characterizes the practice of an expert in the relevant field.²⁰⁴
- Whether the field of expertise claimed by the expert is known to reach reliable results for the type of opinion the expert would give. *Daubert's*

¹⁹⁹ Fed. R. Evid. 702 advisory committee's note (2000).

²⁰⁰ Leesfield and Sylvester, "Admissibility of Expert Testimony: What's Next?"

²⁰¹ Fed. R. Evid. 702 advisory committee's note (2000), discussing *Daubert v. Merrell Dow Pharmaceuticals, Inc.*, 509 U.S. 579, 597 (1993).

²⁰² Fed. R. Evid. 702 advisory committee's note (2000), discussing *General Electric Company v. Joiner*, 522 U.S. 136, 146 (1997).

²⁰³ Fed. R. Evid. 702 advisory committee's note (2000), discussing *Sheehan v. Daily Racing Form, Inc.*, 104 F.3d 940, 942 (7th Cir. 1997).

²⁰⁴ Fed. R. Evid. 702 advisory committee's note (2000), discussing *Kumho Tire v. Carmichael*, 526 U.S. 137(1999).

general acceptance factor does not help show that an expert's testimony is reliable where the discipline itself lacks reliability, as for example, do theories grounded in any so-called generally accepted principles of astrology or necromancy.²⁰⁵

Based upon the above factors, the Supreme Court concluded, "...that the trial judge must have considerable leeway in deciding in a particular case how to go about determining whether particular expert testimony is reliable."²⁰⁶ Yet no single factor is necessarily dispositive of the reliability of a particular expert's testimony.²⁰⁷ If the witness is relying solely or primarily on experience, then the witness must explain how that experience leads to the conclusion reached, why that experience is a sufficient basis for the opinion, and how that experience is reliably applied to the facts.²⁰⁸ Some expert disciplines "have the courtroom as a principal theatre of operations" and as to these disciplines, "the fact that the expert has developed an expertise principally for purposes of litigation will obviously not be a substantial consideration."²⁰⁹

The current Rule 702 was not intended to provide justification for challenges to the testimony of every expert.²¹⁰ In *Kumho Tire*, the trial judge had the discretion:

...both to avoid unnecessary 'reliability' proceedings in ordinary cases where the reliability of an expert's methods is properly taken for granted, and to require appropriate proceedings in the less usual or more complex cases where cause for questioning the expert's reliability arises.²¹¹

²⁰⁵ Id.

²⁰⁶ Id.

²⁰⁷ Fed. R. Evid. 702 advisory committee's note (2000), discussing *Heller v. Shaw Industries, Inc.*, 167 F.3d 146,160 (3d Cir. 1999).

²⁰⁸ Federal Rule of Evidence, 9.

²⁰⁹ Fed. R. Evid. 702 advisory committee's note (2000), discussing *Daubert v. Merrell Dow Pharmaceuticals, Inc.*, 509 U.S. 579, 597 (1993).

²¹⁰ Fed. R. Evid. 702 advisory committee's note (2000).

²¹¹ Fed. R. Evid. 702 advisory committee's note (2000), discussing *Kumho Tire v. Carmichael*, 526 U.S. 137 (1999).

When a trial court applying the amended rule decrees that an expert's testimony is reliable, this does not necessarily mean that contradictory expert testimony is unreliable. When facts are in dispute, experts sometimes reach different conclusions based on competing versions of the facts. The current rule's emphasis on "sufficient facts or data" is broad enough to permit testimony that is the product of competing principles or methods in the same field of expertise.²¹² Expert testimony cannot be excluded simply because the expert uses one test rather than another, when both tests are accepted in the field and both reach reliable results. *Daubert* states that "scientific experts might be permitted to testify if they could show that the methods they used were also employed by 'a recognized minority of scientists in their field'."²¹³ Similarly, "*Daubert* neither requires nor empowers trial courts to determine which of several competing scientific theories has the best provenance."²¹⁴

In *Daubert*, the Court declared that the "focus, of course, must be solely on principles and methodology, not on the conclusions they generate."²¹⁵ Yet as the Court later recognized, "conclusions and methodology are not entirely distinct from one another."²¹⁶ Under the current Rule 702, as under *Daubert*, when an expert purports to apply principles and methods in accordance with professional standards and yet reaches a

²¹² Fed. R. Evid. 702 advisory committee's note (2000), discussing *Heller v. Shaw Industries, Inc.*, 167 F.3d 146, 160 (3d Cir. 1999).

²¹³ Fed. R. Evid. 702 advisory committee's note (2000), discussing *Daubert v. Merrell Dow Pharmaceuticals, Inc.*, 509 U.S. 579, 597 (1993).

²¹⁴ Fed. R. Evid. 702 advisory committee's note (2000), discussing *Ruiz-Troche v. Pepsi Cola*, 161 F.3d 77, 85 (1st Cir. 1998).

²¹⁵ Fed. R. Evid. 702 advisory committee's note (2000), discussing *Daubert v. Merrell Dow Pharmaceuticals Inc.*, 509 U.S. 579, 597 (1993).

²¹⁶ Fed. R. Evid. 702 advisory committee's note (2000), discussing *General Electric Company v. Joiner*, 522, U.S. 136, 146 (1997).

conclusion that other experts in the field would not reach, the trial court may fairly suspect that the principles and methods have not been faithfully applied.²¹⁷

The current rule specifically provides that the trial court must scrutinize not only the principles and methods used by the expert, but also whether those principles and methods have been properly applied to the facts of the case. "Any step that renders the analysis unreliable...renders the expert's testimony inadmissible. This is true whether the step completely changes a reliable methodology or merely misapplies that methodology."²¹⁸ Tethering expert testimony to standards of professional practice will improve the ability of courts to render decisions that are consistent with current medical knowledge. Courts need assistance in interpreting these standards so that judges and juries can make thoughtful and informed considerations of the evidence.²¹⁹

One of the few cases that addressed the *Daubert* reliability approach to bite mark-related evidence is *State v. Swinton*.²²⁰ On a January night in Connecticut, 28 year old Carla Terry left her residence for the evening wearing a black bra, blue jeans, blue shirt, boots, a white hat, and multiple jackets. Her sister had helped her adjust her bra by inserting two safety pins into the right side of the garment. Carla returned that evening from a bar around 2 a.m. to the outside of her apartment. She was then seen walking across the street and out of view. At almost 5 a.m., a police officer discovered her body in a snow bank near the University of Hartford. She was partially dressed, strangled to

²¹⁷ Fed. R. Evid. 702 advisory committee's note (2000), discussing *Lust v. Merrell Dow Pharmaceuticals, Inc.*, 89 F.3d 594, 598 (9th Cir. 1996).

²¹⁸ Fed. R. Evid. 702 advisory committee's note (2000), discussing *Paoli R.R. Yard PCB Litigation*, 35 F.3d 717, 744 (3d Cir. 1994).

²¹⁹ Kassirer, "Inconsistency in Evidentiary Standards for Medical Testimony," 1386.

²²⁰ *State v. Swinton*, 2003 WL 235 15 279 (Conn.).

her death and wrapped in a brown plastic bag. The chief medical examiner observed and photographed crescent-shaped bruises on each of Carla's breasts identified as consistent with bite marks, and later confirmed by a dental forensic specialist.²²¹

Alfred Swinton, the defendant, challenged the admissibility of the photographs of the bite marks on the victim's body that were enhanced using a computer software program (Lucis®) and the images of his teeth superimposed upon those photographs made using Adobe Photoshop®. Swinton contended that the two software programs were introduced through an expert with no more than an elementary familiarity of the programs.²²² Thus, Swinton argued his constitutional right to confrontation was violated.²²³

This case focused on the essence "that reliability must be the watchword" in determining the admissibility of computer-generated evidence in the trial court.²²⁴ The state's scientific expert testified that the computer equipment employed in this case was accepted as standard equipment used in the field of forensic pattern analysis: fingerprint pattern identification, bloodstain pattern identification, footwear and tire impression identification, and bite mark identification. The expert established himself as a qualified computer operator producing the enhancements and his testimony clearly demonstrated that he was well-versed in the software program.²²⁵

The state further presented evidence that proper procedures were followed in connection with the input and output of information of the digitization of the image and

²²¹ Id. at 786.

²²² Id. at 795.

²²³ Id.

²²⁴ Id. at 812.

²²⁵ Id. at 815.

demonstrated to the jury the enhancement process using a laptop. The expert explained that scanning an image changed it from a spatial domain to a frequency domain whereby the image is converted into pixels.²²⁶ Lastly, the state's expert demonstrated that it used a reliable software program.²²⁷ These factors laid an adequate foundation for the bite mark photographs of the victim's body used as evidence in this investigation.

The *Swinton* case established the standard for the authentication of computer-generated evidence because it required testimony demonstrating the reliability of the procedures used to present the computer-generated evidence admitted into evidence. The *Swinton* court acknowledged the computer has tremendous potential for improving our system of justice by generating more meaningful evidence, however "it presents a real danger of being a vehicle of introducing erroneous, misleading and unreliable evidence."²²⁸ The state's expert further testified using several comparative techniques, including *Swinton*'s dental molds, that bite mark identification is based upon the recognition of unique characteristics of the person whose teeth had left that bite mark and that he could actually see the circumferences of the arch, the individual characteristics of many teeth.²²⁹

The *Daubert* decision purports to be concerned about reliability but the term is used differently by forensic scientists. It is highly subjective and raises concerns of personal bias. Thus, it is not uncommon for defense attorneys to challenge any expert's

²²⁶ Id. at 801, FN 15. "A pixel is the smallest discrete element of an image... It is a set of bits that represents a graphic image, with each bit or group of bits corresponding to a pixel in the image. The greater the number of pixels per inch, the greater the resolution."

²²⁷ Id. at 816.

²²⁸ Id at 819, FN 33.

²²⁹ Id at 821.

testimony and exhibits as prejudicial. Courts have been grappling with expert testimony for years. The problem is the legal system has so many approaches and yet wants to be behind the scientific curve. Advancements in digital computer technology are paving the way for perhaps less subjective legal scrutiny. However, as the court in *Swinton* noted, they are not the first court to be concerned with the reliability of computer generated evidence and its technology expands daily. Thus, by the time one digital software program becomes obsolete, a new one takes its place.²³⁰

²³⁰ Id at 819-820.

CHAPTER 4: THE STUDY

The Research Question

The research question at the center of this study will attempt to determine if displacement of eight anterior teeth in the human dentition can be described and quantified using a best-fit curve as a reliable and valid tool for comparing a human bite mark to a suspect's or victim's dentition.

Twenty-five years ago, MacFarlane and his co-workers observed the relationship of individual anterior (front) teeth to the arch form by subjectively assessing 200 stone models of human dentitions using a mean curvature of the canine teeth, with the canine teeth defining the ends of the curve. These anterior teeth (the four incisors) were characterized as being in front of the curve, behind the curve or on the curve.²³¹ MacFarlane described the arch formed by the teeth with reference to the canines. His subjective definition of displacement remains too crude for modern legal proceedings. Courts today expect statistical and scientifically based definitions from expert testimony on the individual dental characteristics of particular teeth found in bite mark evidence. Thus, displacement requires further investigation to be defined for forensic science.

Coronal (crown portion) or incisal (edge) displacement is the visual and measurable vector or linear change observed from the normal proximal position of an erupted human tooth in the maxillary or mandibular bones of the skull. The positional changes of teeth can result from factors such as occlusal disharmonies (abnormal wear patterns), tongue thrust (constant pressure of the tongue when swallowing may force

²³¹ T.W. MacFarlane, D.G. MacDonald and D.A. Sutherland, "Statistical Problems in Dental Identification." Journal of Forensic Science 14 (1974): 247-252.

teeth out of alignment), abnormal eruption patterns and trauma. These phenomena are easily observed by dentists but not easily measured. Defining displacement involves the positional change of teeth in relationship to their own natural curve, and may represent a measurable characteristic to define uniqueness in the human dentition. Often, calculating the distance from where a tooth rests in relation to its natural curve is not the same as displacement.

Distance and displacement are different quantities, but they are related. Distance is a ratio scalar measure of the interval between two foci determined along the actual path connecting them. Displacement is a ratio vector measure of the interval between two locations measured along the shortest path connecting them. This can perhaps best be described using a common example. When a person walks around a desk, sometimes the distance walked is the same as the magnitude of the displacement. Yet as steps are traced completely around the desk, the distance and displacement of the journey soon begin to diverge. The distance traveled increases uniformly, but the displacement fluctuates and then returns to zero. It is important that both be considered when evaluating a best-fit curve for measuring displacement of the anterior teeth in bite mark evidence.

This study began with a thorough word search for the term “displacement” to see if it had been defined dentally.²³² The search produced no literature relevant to displacement of anterior (front) teeth in the human dentition. Thus, no published methodologies or statistical studies have scientifically defined “displacement” of the anterior teeth. While the term “displacement” may be used in courts by dental forensic experts in describing a tooth characteristic, it remains undefined in dental and forensic

²³² With the assistance of Rosemary Del Toro, reference librarian at Raynor Memorial Libraries/Research and Outreach Services.

communities and needs valid and reliable scientific methodology to pass the muster of legal scrutiny.

As dental forensic research grows, experts will be able to inform courts about the strengths and weaknesses of their theories and methodologies and be able to apply their work to individual cases. Statistical data is needed of dental variations that occur in different populations and to further develop computer-generated pattern recognition software for identification of dental forensic sciences. When human matches are identified, dental forensic scientists could compute and report random-match probabilities similar to those used in DNA typing. Together with error rates, these estimates could provide courts about the probative value of the evidentiary dental forensic match.

Thus, this study was conducted in an effort to support a basic research model similar to DNA typing where scientists tested the core assumptions in their field. Determining if displacement of the anterior teeth in the human dentition can be described and quantified using a best-fit curve, as a reliable and valid tool for comparing a human bite mark to a suspect's or victim's dentition, is only the beginning to placing sound science into dental forensic identification of bite mark evidence.

Materials and Methods

Teeth in Question

The teeth to be considered in measuring displacement in a bite mark are the four lateral and four central incisors (anterior teeth) in the human dentition. The anterior (front) teeth in the human dentition are comprised of four mandibular (lower) and four maxillary (upper) incisors and four cuspid or canine teeth. The imprints of the anterior teeth #23-#26 are measured for the mandibular dentition as shown in Figure 7 while the imprints of anterior teeth #7-#10 are those measured in this study for the maxillary (upper) dentition as shown in Figure 8.

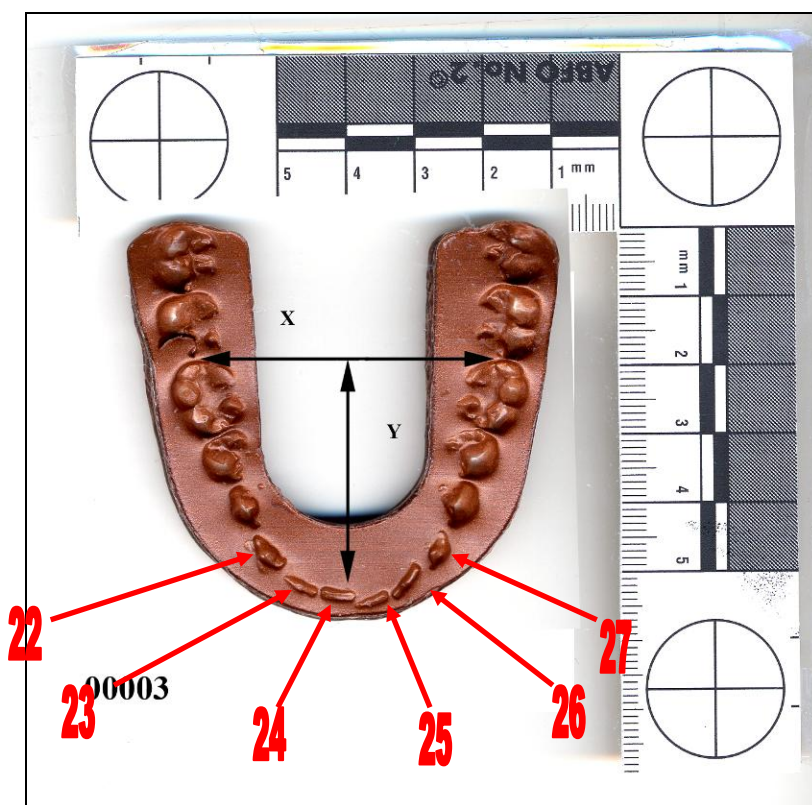


Figure 7: Within a scale for accuracy, this represents a dental wax imprint of a mandibular arch taken from a volunteer tagged as 00003. The numbers represent the teeth according to the universal numbering system.

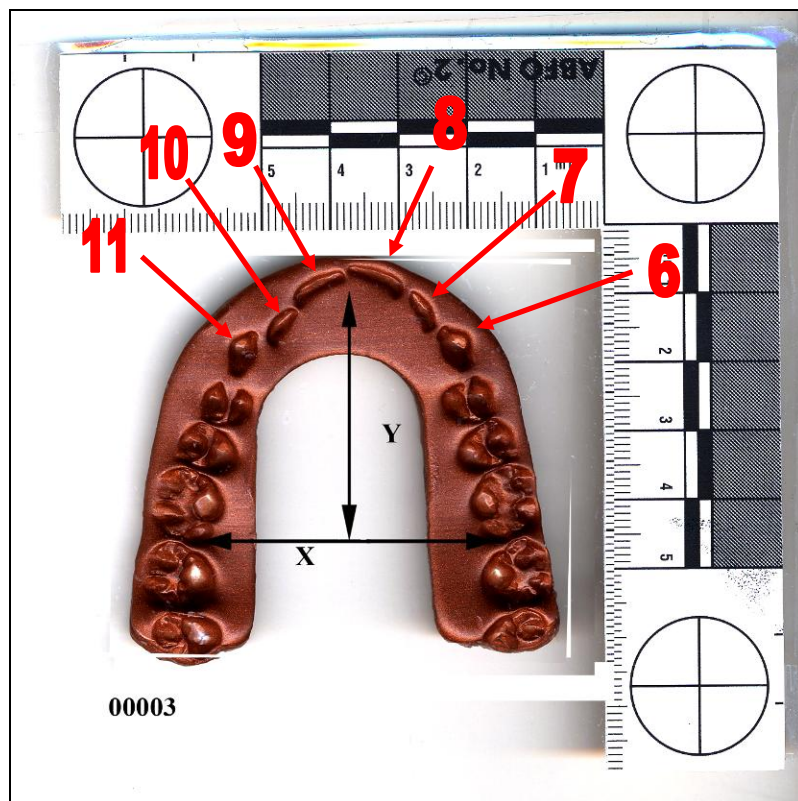


Figure 8: Within a scale for accuracy, this represents a dental wax imprint of a maxillary arch taken from a volunteer tagged as 00003. The numbers represent the teeth according to the universal numbering system.

Mathematical Curves to Measure Displacement

A human bite imprint is described as an elliptical or circular injury that records the specific characteristics of the anterior teeth.²³³ It may be composed of two c-shaped arch forms separated at their bases by an open space as highlighted in Figure 9 (next page).

²³³ David Sweet, "A Look at Forensic Dentistry-Part 2: Teeth as Weapons of Violence-Identification of Bitemark Perpetrators." 416.



Figure 9: Photograph of bite marks on human skin (Courtesy of Knox and Associates.)

Because of the particular shape characteristic of a human bite mark, three mathematical curves were used in this study to determine if a best-fit curve for each individual arch could be achieved and to provide a methodology to measure the displacement of the anterior teeth in the human dentition from each curve. The three curves chosen for this study include the cubic Bezier, polynomial and ellipse curves because they are commonly used in computer graphics and are easy to generate mathematically.

- The Bezier Curve

In numerical analysis, the Bezier curve is a parametric curve important in computer graphics²³⁴ because it generates smooth curves. French engineer Pierre Bezier patented this curve in 1962 when he was designing automobiles for Renault. The Bezier curve, however, was developed three years earlier in 1959 by Paul de Casteljaou using his own algorithm.²³⁵ Modern imaging graphic systems such as Adobe PostScript[®] and Adobe Illustrator CS2[®] use cubic Bezier curve shapes. A cubic Bezier curve is defined by four points.²³⁶

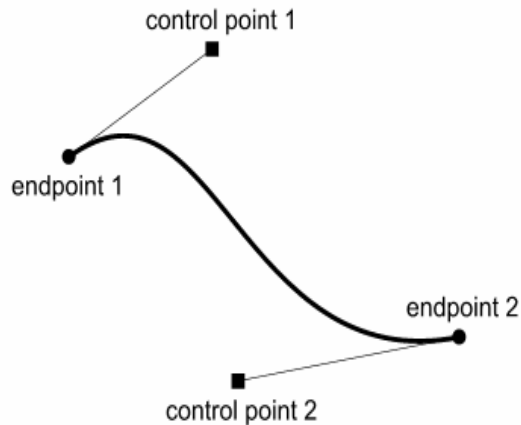


Figure 10: Basic components of a cubic Bezier curve. (Per conversation Dr. Gary Krenz)

Endpoints (x_0, y_0) serve as the origin end points and (x_3, y_3) are the destination end points. The points (x_1, y_1) and (x_2, y_2) are control points. Two equations define the points on the curve. Both are evaluated for an arbitrary number of values of t between 0 and 1. One equation yields values for x ; the other yields values for y . As increasing values for t

²³⁴ Ward Cheney and David Kincaid, Numerical Mathematics and Computing, 4th Edition (1999): 364.

²³⁵ <http://www.ams.org/samplings/features-column/fcarc-bezier>

(Last visited May 2010 with Dr. Krenz).

²³⁶ <http://www.drdoobbs.com/184403417> (Last visited May 2010 with Dr. Krenz).

are supplied to the equations, the point defined by $x(t),y(t)$ moves from the origin to the destination. This is how the equations are defined in Adobe's PostScript® references:

$$\begin{aligned}x(t) &= a_x t^3 + b_x t^2 + c_x t + x_0 \\x_1 &= x_0 + c_x / 3 \\x_2 &= x_1 + (c_x + b_x) / 3 \\x_3 &= x_0 + c_x + b_x + a_x \\y(t) &= a_y t^3 + b_y t^2 + c_y t + y_0 \\y_1 &= y_0 + c_y / 3 \\y_2 &= y_1 + (c_y + b_y) / 3 \\y_3 &= y_0 + c_y + b_y + a_y\end{aligned}$$

This method of definition can be reverse-engineered so that it will yield the coefficient values based on the points described in the preceding equation:

$$\begin{aligned}c_x &= 3 (x_1 - x_0) \\b_x &= 3 (x_2 - x_1) - c_x \\a_x &= x_3 - x_0 - c_x - b_x \\c_y &= 3 (y_1 - y_0) \\b_y &= 3 (y_2 - y_1) - c_y \\a_y &= y_3 - y_0 - c_y - b_y\end{aligned}$$

By knowing coordinates for any four points, one can create the equations for a simple Bezier curve.²³⁷

²³⁷ PostScript® Language Reference Manual, Adobe Systems Incorporated, 3rd Edition (1999).

- The Polynomial Curve

René Descartes in *La Géométrie* (1637) introduced the concept of the graph for the basic polynomial equation $y = ax^2 + bx + c$ (see Figure 11). He popularized the use of letters from the beginning of the alphabet to denote constants and the use of letters from the end of the alphabet to denote variables used in the formula for a polynomial curve; he also introduced the use of superscripts to denote exponents.²³⁸ Descartes' influence allowed geometric shapes to be expressed in algebraic equations.

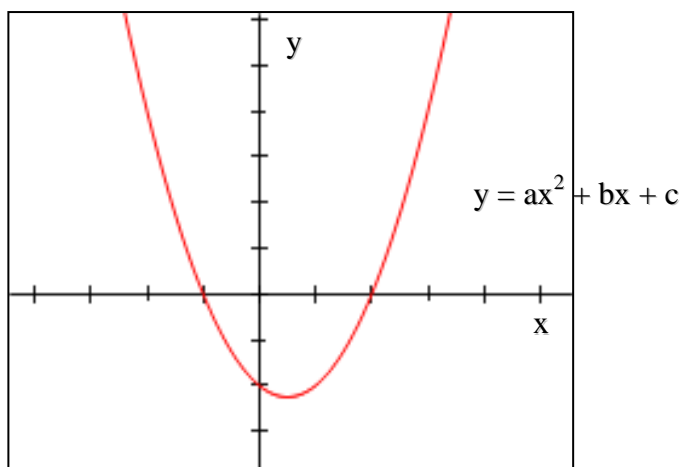


Figure 11: Basic polynomial curve (Courtesy of Earl Swokowski)

- The Ellipse Curve

The ellipse is a closed curve consisting of all points where the distances from each of two fixed points (foci) add up to the same value. The midpoint between the foci is the center. One property of an ellipse is that the reflection off its boundary of a line from one focus will pass through the other.

In computer graphics, the ellipse can be drawn in the Macintosh QuickDraw API[®], the Windows Graphics Device Interface[®] (GDI) and the Windows Presentation

²³⁸ <http://mathdl.maa.org/mathDL/46/> (Last visited May 2010 with Dr. Krenz).

Foundation® (WPF).²³⁹ Jack Bresenham at IBM was well-known for his invention of one of the earliest algorithms discovered in the field of computer graphics for drawing an ellipse; however, an efficient generalization to draw ellipses was invented in 1984 by Jerry Van Aken²⁴⁰ and is depicted in Figure 12. An oval may or may not fit the definition of an ellipse yet an ellipse often appears like an oval.

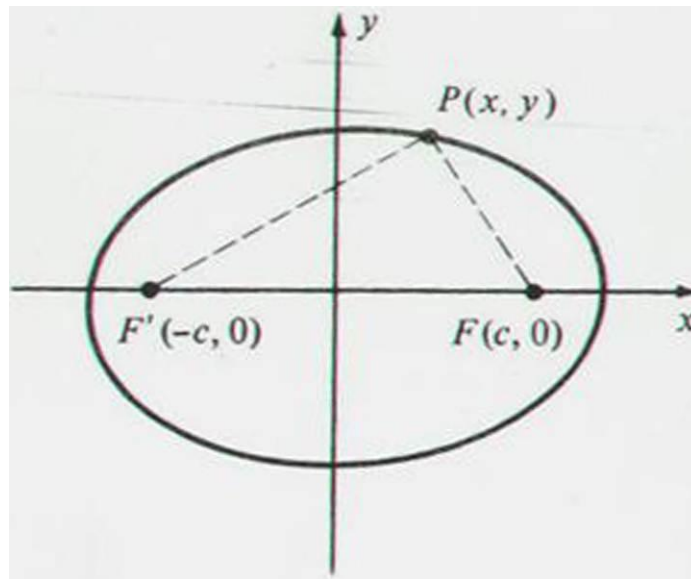


Figure 12: Schematic view of an ellipse curve (Courtesy of Earl Swokowski)

²³⁹ M.L.V. Pitteway, “Algorithm for drawing ellipses or hyperbolae with a digital plotter” *Computer Journal*, 10 (1967): 282-289.

²⁴⁰ <http://portal.acm.org/citation.cfm?id=282943> (Last visited May 2010 with Dr. Krenz).

Defining Displacement: Need for a Decision Tree

Since there is no current literature on the displacement of the anterior teeth in the human dentition, a decision tree (Figure 13), often used in law, was used to rationalize how displacement was defined in this study. The canine teeth were used as starting points for generating the Bezier, polynomial, and ellipse curves. Each incisor can be missing or present. When the incisor was present, it was evaluated whether it was displaced or not displaced from the three computer-generated curves placed individually on each arch. An incisor is not displaced if the center point of the tooth falls directly on the curve. When an incisor is displaced, it is either displaced labially (lip side) or lingually (tongue/palate side) in the human mouth. Statistically, the number of possible permutations of the eight incisors is 4^8 or 65,536. The probability of each incisor/displacement combination is $1/65,536$ or 0.000015. Therefore, the probability of two persons having the same incisor/displacement permutation is less than 0.000015. This statistic makes displacement of the anterior teeth another important dental variable to contribute to the validity and reliability of forensic odontology in the courtroom.

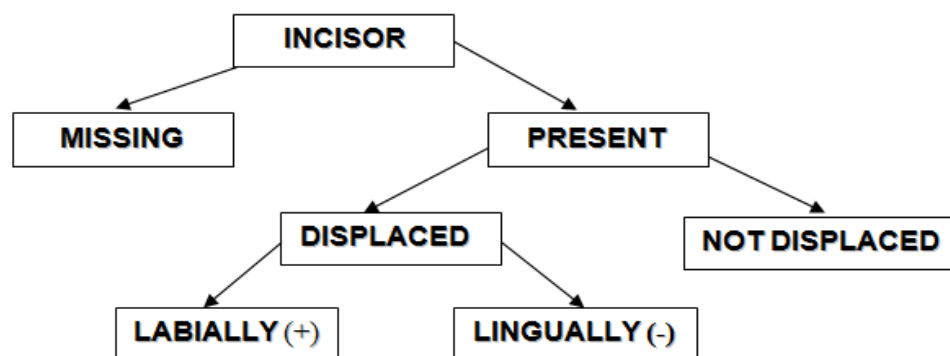


Figure 13: Decision tree used for determining displacement

Creating the Exemplars

The sample studied was taken from a larger convenience sample of waxed dental imprints or exemplars used to develop a methodology for the generation of a dataset of human dental characteristics. (Appendix C) All of the exemplars were scanned into an Epson 1680 professional-grade scanner at a resolution of 300 pixels per inch (ppi). The dental exemplars were produced from an American Dental Association-approved, coppered-colored, wax-wafer material and used to record the bite imprints of a male population of military personnel ages 18-44 from two National Guard units in Wisconsin.

The brand of wax-wafer used for the dental exemplars was Surgident Coprwx[®], which is impregnated with copper powder to provide uniform heat transmission during the warming and cooling process. It is purchased in a pre-cut, arch-shaped wafer containing a middle layer of aluminum foil to increase strength, prevent teeth from cutting through the middle, and reduce distortion. Each wafer was softened in warm water (52-57 degrees Celsius) before being placed in the volunteer's mouth. After the dental exemplar registered the volunteer's teeth imprint on both sides, it was sprayed with a disinfectant, air-dried, placed in a labeled, sterile bag, and refrigerated to prevent distortion until the scanning procedure occurred.

Imaging the Exemplars

Figure 14 shows an ABFO, eight-inch, #2-scale placed with each dental wax exemplar to verify the proper imaging of the dental exemplar when scanned. All of the dental exemplar scans were saved as a read-only image in a .psd format for use in Adobe Photoshop®.²⁴¹

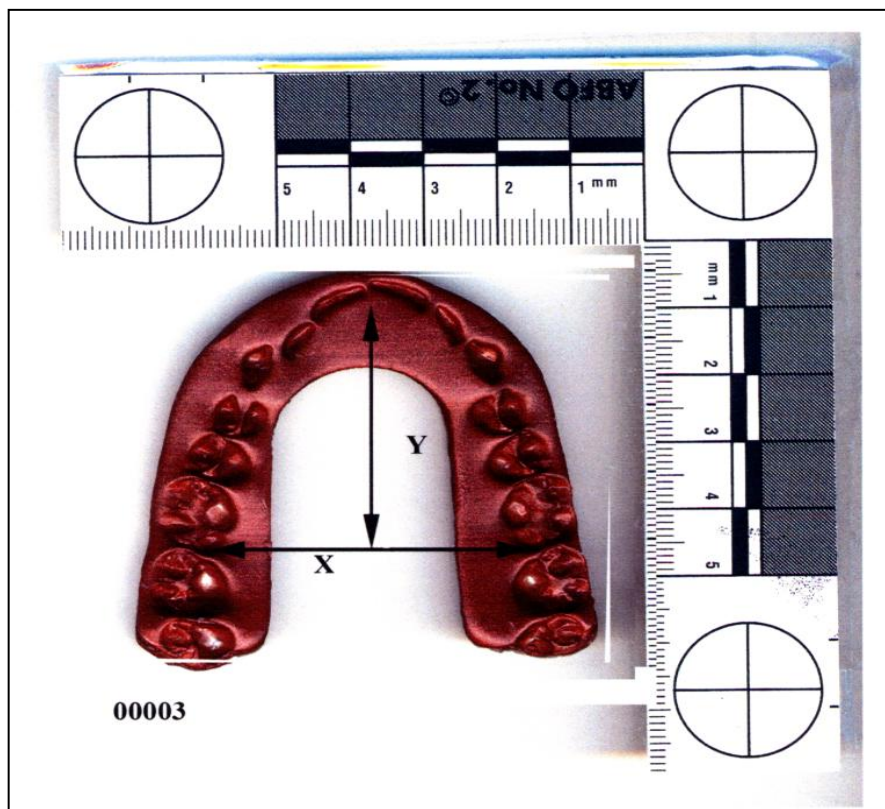


Figure 14: Wax exemplar and ABFO ruler for accuracy

²⁴¹ L.T. Johnson et al., “Quantification of a Database of the Human Dentition: Methodology” *Journal of Forensic Identification* 58:4 (August 2008): 409-416.

Two imaging specialists²⁴² from the Wisconsin Crime Laboratory in Milwaukee, Wisconsin, utilized the FBI's Scientific Working Group on Imaging Technology guidelines to ensure quality-control of the digital images recorded for each dental exemplar in the sample population measured. The imaging experts calibrated the scanner for accuracy and reliability. Intra-operator consistency was validated by repeating measurements of 10 percent of randomly chosen, completed exemplar files. Duplicate scans of 150 exemplars (75 dentitions) were retrieved from the dataset.²⁴³ Using the

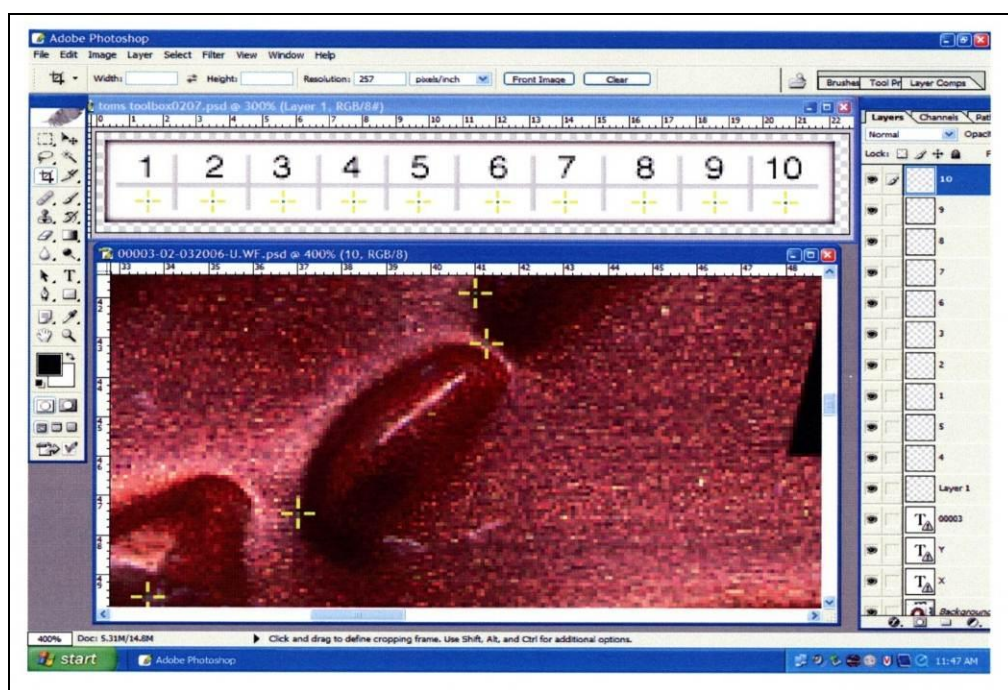


Figure 15: The imaging software program allowed for the ten “+” crosshairs to be placed on the mesial and distal aspects of either side of the tooth for each exemplar.

²⁴² Id. Wisconsin Crime Lab Forensic Imaging Specialists Dave Cadle and Aaron Matson conducted the quality controls.

²⁴³ Id.

forensic industry standard in image processing, the Adobe Photoshop CS[®] software allows crosshairs or pluses (“+”) to be manually placed on either side (mesial and distal points) of each of the four anterior teeth. The center or midpoint of each canine tooth in the dental exemplars received a designated crosshair as well. A total of ten crosshairs were placed on each arch.

Utilizing the Wirtz Program: Generating the Three Curves

The Wirtz software program was developed by Tom Wirtz, Director of Dental Informatics at Marquette University School of Dentistry, to assist this study's objectives. The Wirtz software program determined the center or midpoint of every anterior tooth in the sample by reading the placement of the tooth's particular colored crosshair placed on each side (mesial and distal) of the anterior incisors.²⁴⁴ The program then used these points to calculate the Bezier, polynomial and ellipse curves for each of the samples examined. The inclusion criteria for the dental exemplars used in this study required that all anterior teeth be present so that the Wirtz software program could accurately read the correct crosshair designated by a number and color assigned to it.

²⁴⁴ L.T. Johnson et al., "Quantification of a Database of the Human Dentition: Methodology" 409-416.

- The Bezier Curve

To further explain this process, four points P_0 , P_1 , P_2 , P_3 in the plane define the cubic Bezier curve. Spanning from left to right, the points include P_0 (center of cuspid tooth #11 or #22), P_1 (center of anterior tooth #9 or #24), P_2 (center of anterior tooth #8 or #25), and P_3 (center of cuspid tooth #6 or #27).

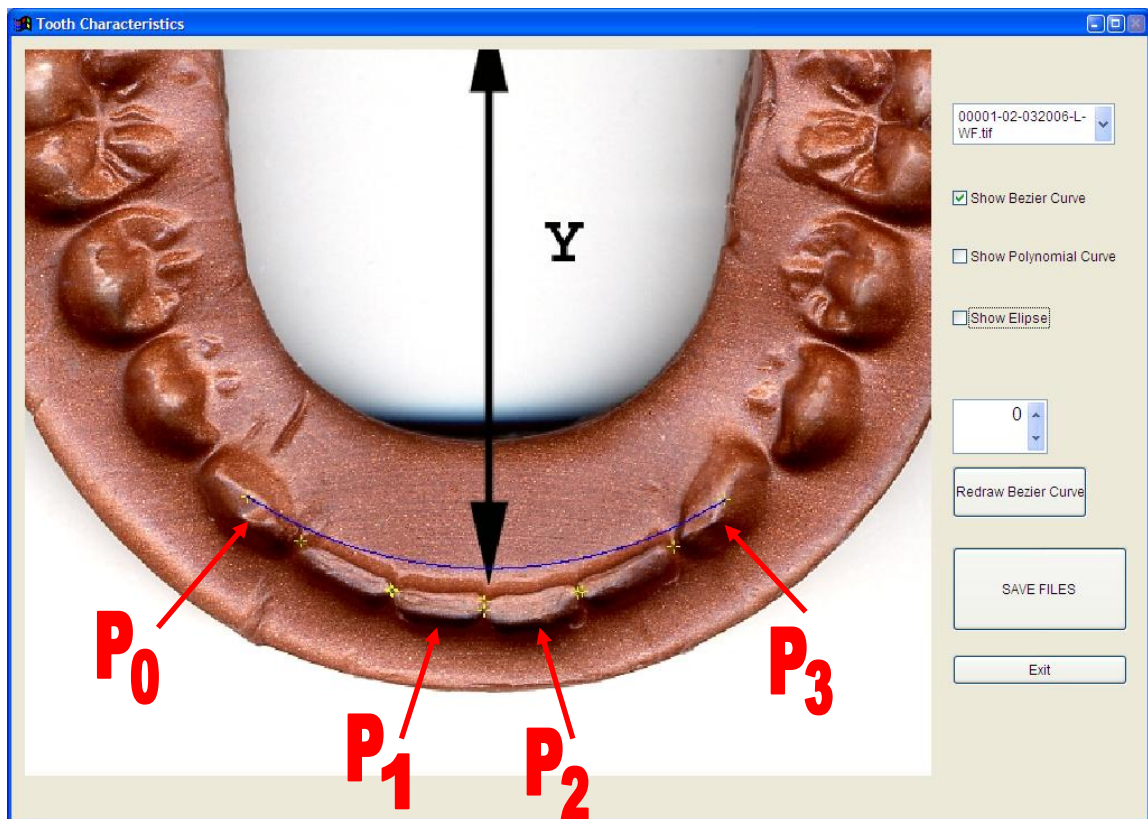


Figure16: Four points (P_0 , P_1 , P_2 and P_3) define the Bezier curve in blue.

On the x/y coordinate, the curve is calculated by determining the y value for the range of pixels on the x axis between P_0 and P_3 using the mathematical equation: $Bt = P_0(1-t)^3 + 3P_1t(1-t)^2 + 3P_2t^2(1-t) + P_3t^3$, $t \in [0,1]$. The curve starts at P_0 going towards P_1 and arrives at P_3 coming from the direction of P_2 . Generally, the curve will not pass

through P_1 or P_2 ; these points are only present to provide directional information. The distance between P_0 and P_1 determines how far the curve will move in the direction of P_2 before turning towards P_3 .

In this study, the Bezier curve always appeared lingual to the dental arch curve; thus, the Wirtz software program allowed for the Bezier curve to be adjusted by increasing the number in the designated window shown in red of Figure 17. The adjustment ranged from 0 to 100. At 0, no adjustment was made. From 1 to 100, points P_1 and P_2 were incrementally extended on the y axis as a percentage of the distance on the y-axis from the respective point to the two base points. So at 53, point P_1 was extended to moved to $(P_1 \text{ current vertical location from base points } P_0 \text{ and } P_3 + .53 * P_1 \text{ current vertical location from base points } P_0$

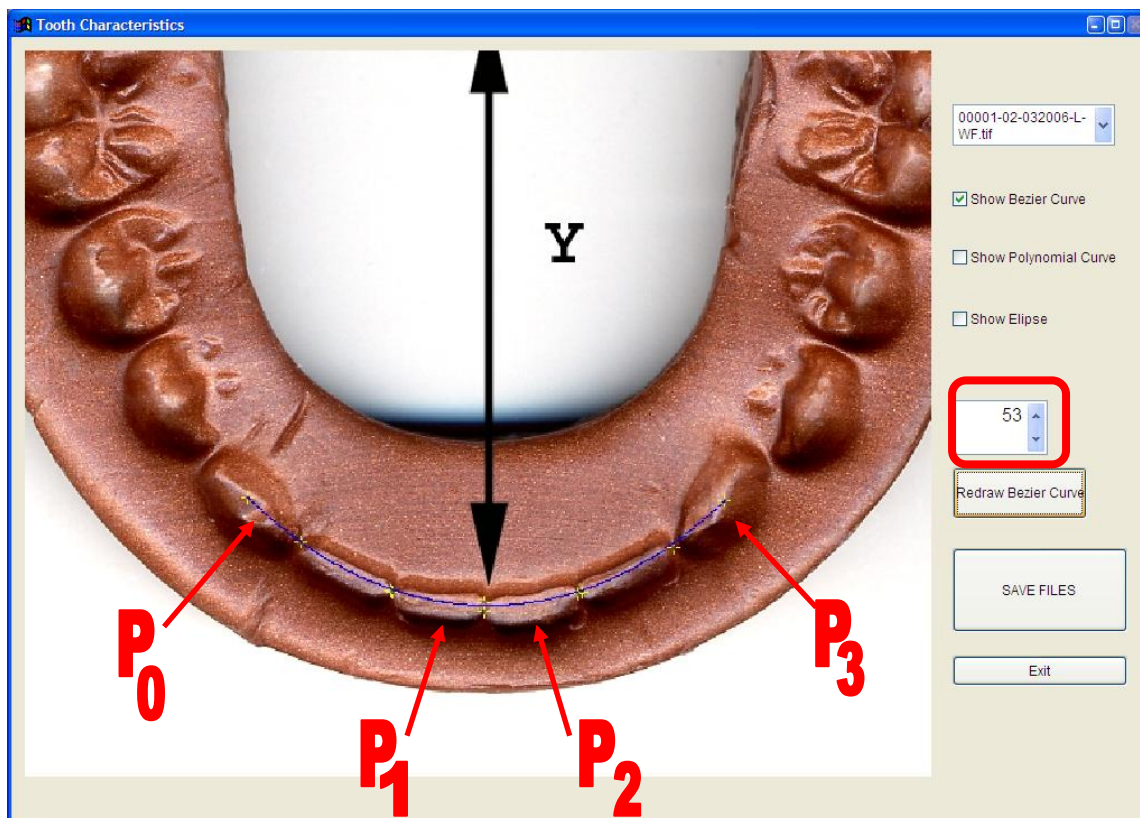


Figure 17: An adjustment of 53% (displayed in the red box) for the blue Bezier curve

and P_3). This moved the Bezier curve up or down from its original position to achieve the best fit for each dental arch. The amount of adjustment was recorded and saved with each screen capture.

- The Polynomial Curve

Six points $P_0, P_1, P_2, P_3, P_4, P_5$ in the plane define the polynomial curve. These points correspond to the center points of the six anterior teeth. The polynomial curve was computer-generated using the mathematical equation: $y = ax^2 + bx + c$. The complete formula is described in Appendix A.

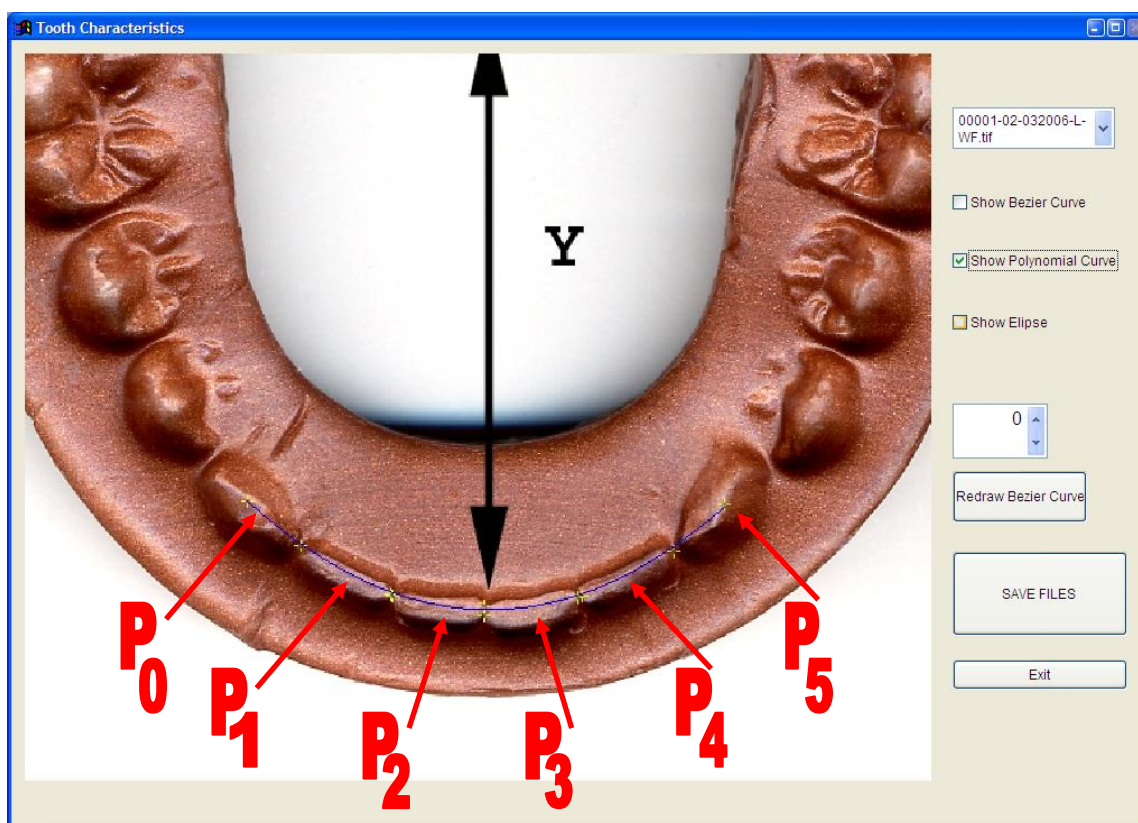


Figure 18: The six points (P_0, P_1, P_2, P_3, P_4 and P_5) define the polynomial curve shown in blue.

- The Ellipse Curve

The ellipse curve is defined by three points: P_0 (cuspid center point of tooth #11 or tooth #22), P_1 (cuspid center point of tooth #6 or tooth #27), and P_2 (center point between mesial points of teeth #8 and #9 or center point between mesial points of teeth #24 and #25). The complete mathematical formula for the ellipse curve is described in Appendix B.

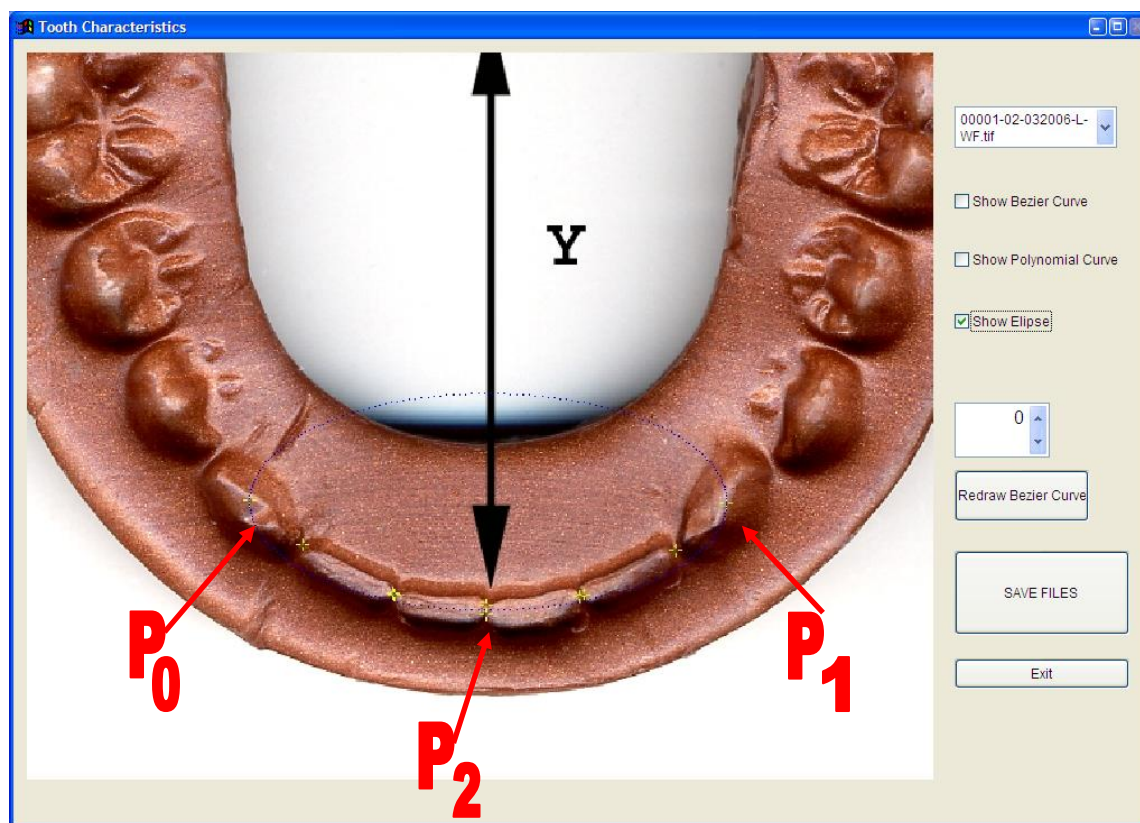


Figure 19: Three points (P_0 , P_1 and P_2) define the ellipse curve shown in blue.

Measuring Displacement

In this study, displacement was determined on the basis of where the center or midpoint of each anterior tooth resides in relationship to the computer-generated blue curves. The Wirtz software program calculated and placed a pink pixel or dot in the center of the tooth. When the center of the tooth fell on the curve, the tooth was not considered displaced and was recorded as zero. (Figure 20)

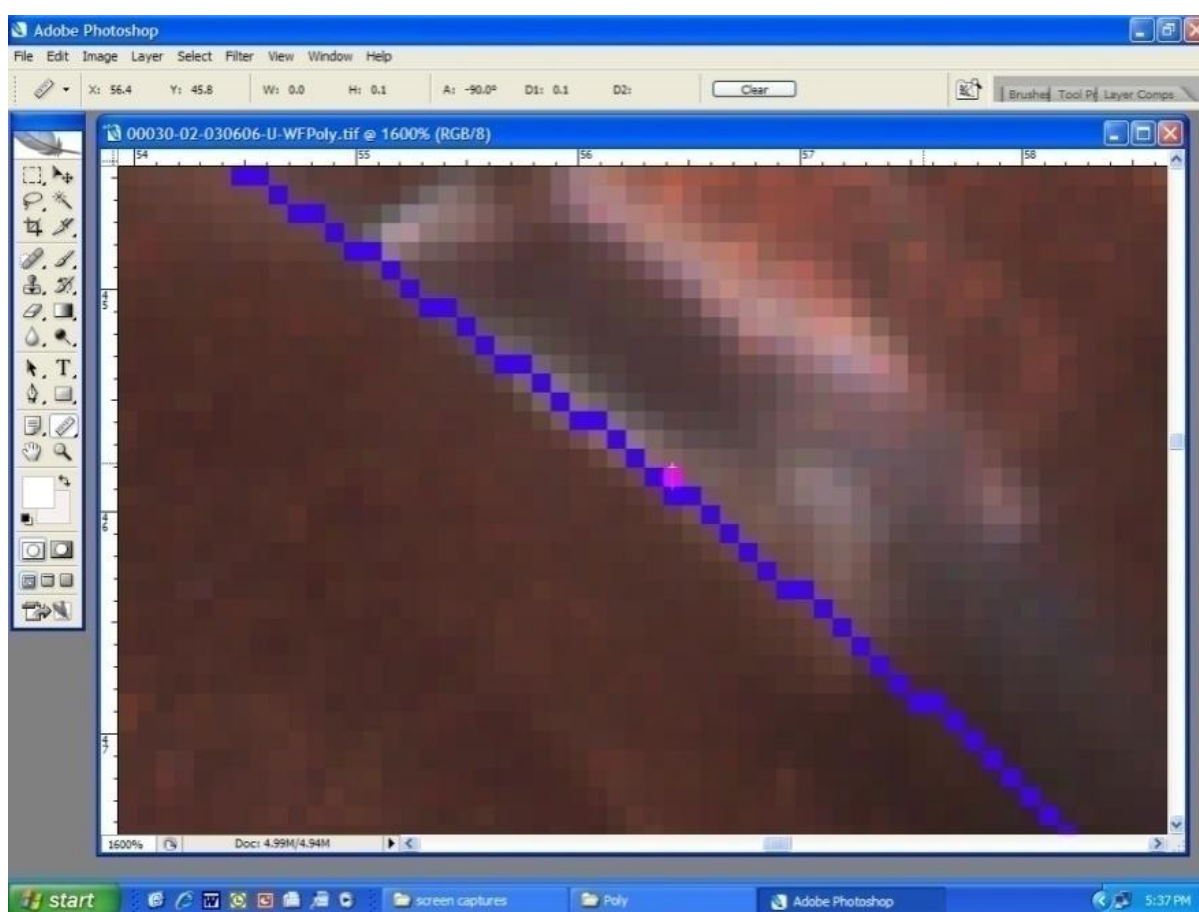


Figure 20: Magnification shows the pink center point pixel on a tooth and its relationship to the blue curve line.

The recorded measurement was negative when the center of the tooth was inside the curve (lingual).

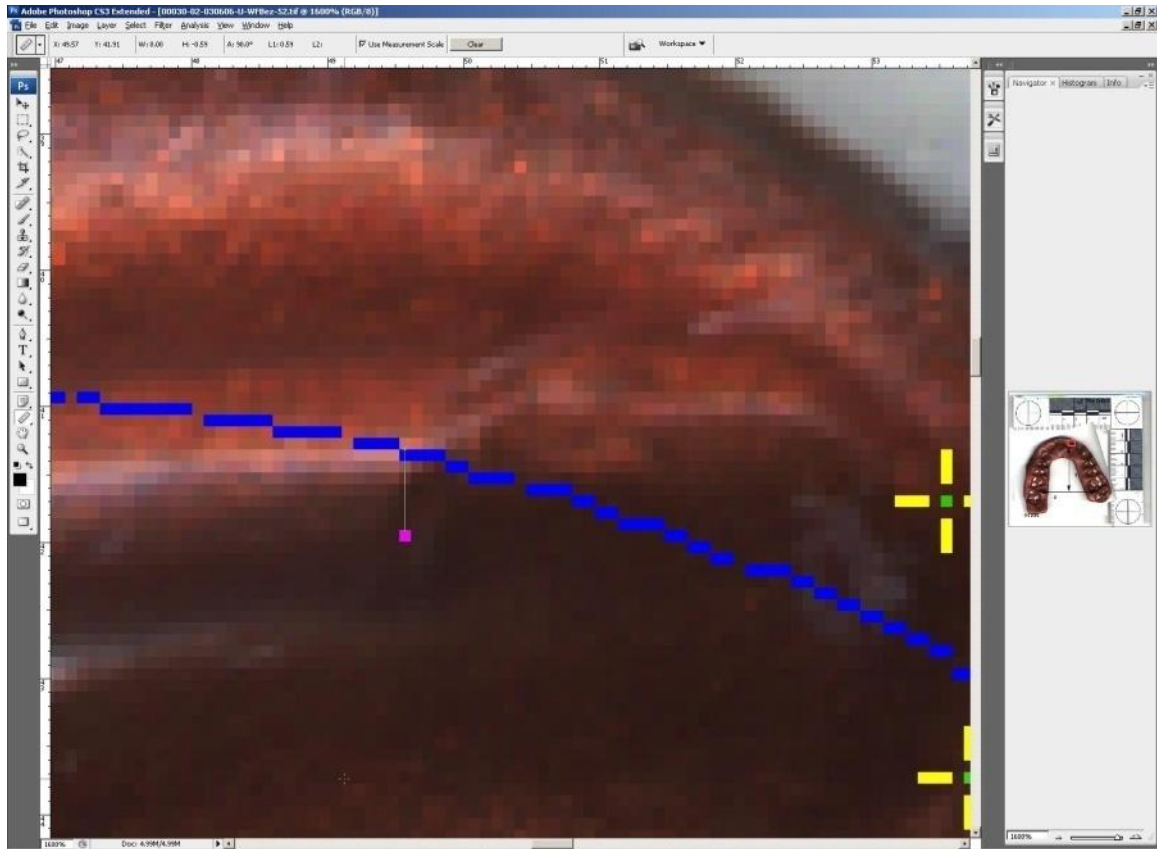


Figure 21: Magnification of the pink center pixel point inside the blue curve on a tooth

When the center of the tooth fell outside the curve (labial), the recorded number was positive.

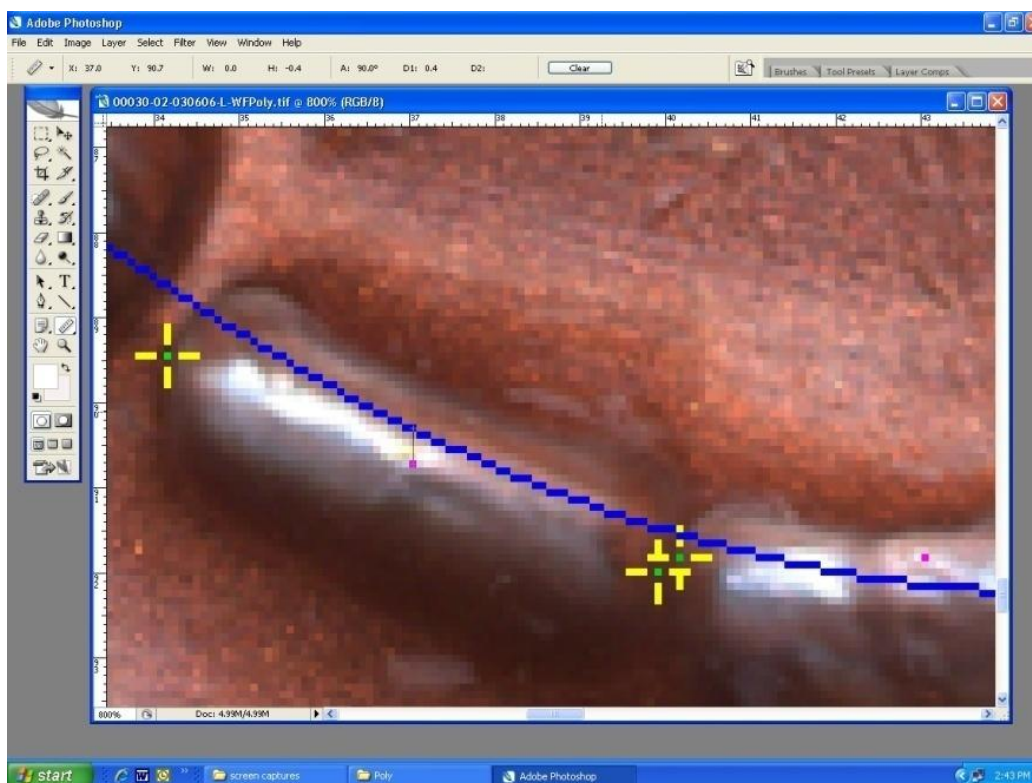


Figure 22: Magnification of the pink center pixel point outside the blue curve of a tooth

Adobe Photoshop® enabled three measurements for each anterior tooth whereby the mesial, center and distal crosshairs were drawn using the measuring tool and recorded at a vertical, 90-degree angle to each of the three curves. (Figure 23)

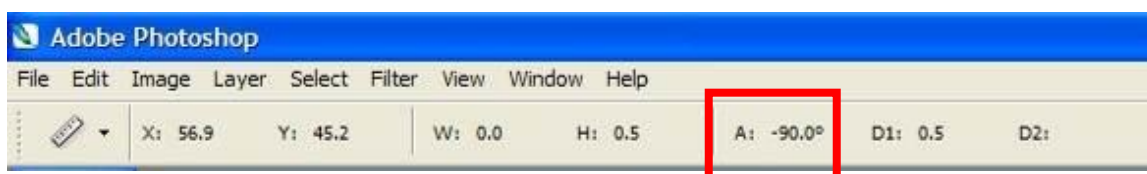
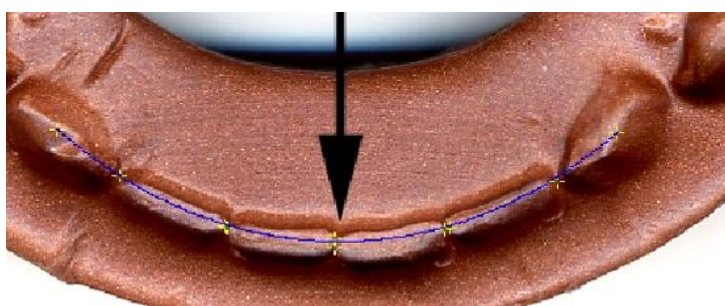
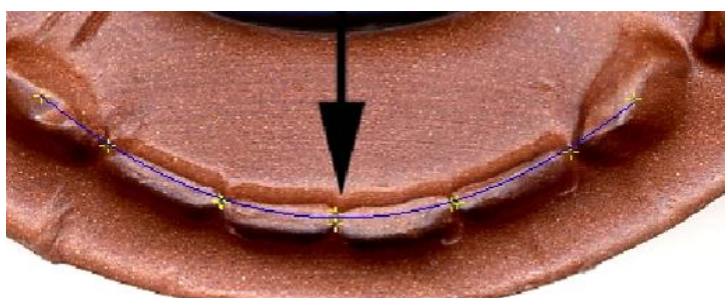


Figure 23: The red box displaying the angle used in the measurements

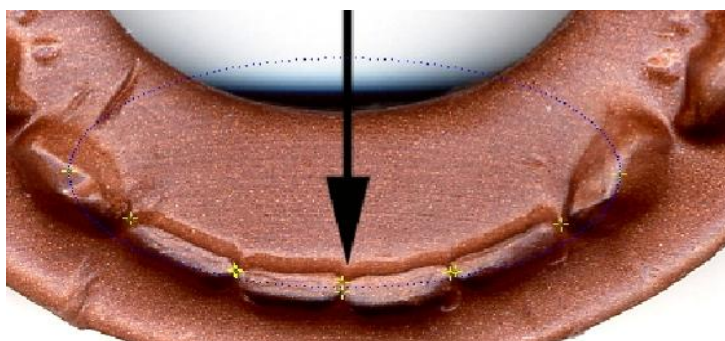
The measurements for each tooth to the three curves were recorded on an Excel data entry sheet. The Print Key[®] software program saved the screen captures of the measurements for each area of the tooth measured. This provides quality assurance and allowed the measurements to be reviewed for accuracy.



Bezier Curve



Polynomial Curve



Ellipse Curve

Figure 24: Each of the three curves was applied using digital technology

All three computer-generated curves were digitally applied to each of the 75 wax exemplars to measure the tooth displacement for each arch. (Figure 24) Only the Bezier curve could be manually adjusted to best fit the individual arches. Adjusting the Bezier

curve to better fit each individual's mouth created a level of subjectivity in the methodology process. With the data recorded on an Excel™ sheet, the results of the measurements for each tooth and each curve were then statistically analyzed by Evelyn Kuhn and Lui Hua, Outcome Statistical Analysts at Children's Hospital of Wisconsin Healthcare Systems in Milwaukee, Wisconsin. The results of their analysis are displayed in the following tables.

Results: The mean, standard deviation and range values for the distal (D), center (C) [shaded] and mesial (M) measurements of each numbered anterior tooth for the Bezier, polynomial and ellipse curves are shown in Tables 1, 2 and 3.

Variable	N	Mean	Standard Deviation	Minimum	Median	Maximum
D23	75	0.03	1.03	-3.55	0.08	2.62
C23	75	-0.37	0.75	-2.96	-0.34	1.27
M23	75	-0.24	0.76	-2.46	-0.17	2.46
D24	75	-0.01	0.5	-1.1	0	2.03
C24	75	-0.46	0.4	-1.86	-0.42	0.51
M24	75	-0.42	0.66	-2.54	-0.34	1.19
M25	75	-0.49	0.79	-2.54	-0.42	1.7
C25	75	-0.5	0.5	-2.2	-0.51	0.76
D25	75	-0.05	0.42	-1.27	-0.08	1.1
M26	75	-0.1	0.59	-1.86	-0.08	1.35
C26	75	-0.2	0.73	-2.79	-0.17	2.54
D26	75	0.25	1.25	-3.82	0.25	4.32
D7	75	0.24	1.24	-2.96	0.25	4.23
C7	75	-0.25	0.86	-2.88	-0.17	1.52
M7	75	-0.08	0.91	-2.37	-0.17	1.78
D8	75	0.21	0.66	-1.61	0.17	1.86
C8	75	-0.39	0.4	-1.19	-0.42	0.93
M8	75	-0.02	0.72	-1.35	-0.08	4.06
M9	75	0.02	0.72	-1.27	0	2.54
C9	75	-0.37	0.32	-1.1	-0.42	0.85
D9	75	0.15	0.61	-1.52	0.17	1.61
M10	75	0.12	0.99	-3.64	0.17	2.71
C10	75	-0.09	0.9	-3.22	-0.08	2.37
D10	75	0.23	1.08	-3.39	0.25	3.3

Table 1: Bezier curve results (D: distal point; C: center point; M: mesial point of each tooth).

Variable	N	Mean	Standard Deviation	Minimum	Median	Maximum
D23	75	0.29	0.82	-2.4	0.3	2.4
C23	75	-0.02	0.52	-1.8	0.1	1.1
M23	75	0.16	0.66	-1.4	0.2	2.9
D24	75	0.36	0.61	-0.5	0.3	2.8
C24	75	-0.09	0.45	-1.3	-0.2	1.5
M24	75	-0.05	0.66	-1.7	-0.2	1.8
M25	75	-0.09	0.68	-2.5	-0.1	1.3
C25	75	-0.13	0.46	-2.4	-0.2	0.8
D25	75	0.32	0.53	-1.7	0.3	1.5
M26	75	0.26	0.57	-1.5	0.2	1.9
C26	75	0.12	0.55	-1.9	0.2	2
D26	75	0.47	1.05	-2.9	0.5	3.7
D7	75	0.78	0.88	-1.3	0.7	3.6
C7	75	0.41	0.53	-1.2	0.4	1.4
M7	75	0.47	0.74	-1.5	0.4	2.1
D8	75	0.75	0.83	-2.2	0.8	3.4
C8	75	-0.14	0.43	-0.9	-0.2	1.4
M8	75	0.08	0.73	-1.3	0.1	3.2
M9	75	0.1	0.68	-1.5	0.1	1.8
C9	75	-0.16	0.35	-0.9	-0.2	1
D9	75	0.59	0.78	-1.4	0.6	2.4
M10	75	0.56	0.79	-2.4	0.6	2.6
C10	75	0.44	0.62	-1.7	0.4	2.2
D10	75	0.65	0.82	-1.9	0.6	2.9

Table 2: Polynomial curve results (D: distal point; C: center point; M: mesial point of each tooth).

Variable	N	Mean	Standard Deviation	Minimum	Median	Maximum
D23	75	-0.84	0.93	-3.9	-0.68	1.02
C23	75	-0.73	0.78	-3.05	-0.68	1.27
M23	75	-0.14	0.91	-2.03	-0.17	3.39
D24	75	0.09	0.79	-1.11	0	3.05
C24	75	-0.08	0.5	-1.1	-0.17	1.35
M24	75	0.05	0.49	-1.44	0	1.69
M25	75	-0.01	0.5	-1.61	0.08	1.52
C25	75	-0.2	0.45	-1.69	-0.17	0.93
D25	75	-0.09	0.69	-1.69	-0.08	1.61
M26	75	-0.16	0.83	-3.13	-0.08	1.95
C26	75	-0.78	0.82	-3.73	-0.68	1.86
D26	75	-0.9	1.18	-5.17	-0.93	3.22
D7	75	-1.5	1.26	-4.23	-1.35	3.3
C7	75	-1.49	0.94	-3.81	-1.52	0.59
M7	75	-0.84	1	-3.98	-0.59	1.61
D8	75	-0.46	1.14	-5.16	-0.42	2.03
C8	75	-0.55	0.62	-2.46	-0.51	0.68
M8	75	-0.03	0.31	-0.93	-0.08	1.02
M9	75	0.02	0.31	-1.02	0	0.85
C9	75	-0.54	0.57	-2.88	-0.42	0.68
D9	75	-0.51	1.07	-4.4	-0.42	1.86
M10	75	-0.66	1.09	-5.42	-0.51	2.46
C10	75	-1.34	1.04	-5.85	-1.19	0.93
D10	75	-1.46	1.18	-6.19	-1.35	1.02

Table 3: Ellipse curve results (D: distal point; C: center point; M: mesial point of each tooth).

Figures 25 through 32 depict box plots of the center point (C) measurements for the Bezier (B), polynomial (P) and ellipse (E) curves that were developed for the total number of exemplars ($N = 75$) in each graph using the statistical software program SPSS (Statistical Package for the Social Sciences). In each figure, the tooth number is identified on the left side of each graph. The shaded boxes represent the 25th - 75th percentiles. The horizontal line in the box represents the median. The “whiskers” extend to the smallest and largest values that are not outliers. Outliers (small circles) are 1.5 - 3 box-lengths from the 25th or 75th percentiles. Extreme values (asterisks) are values more than 3 box-lengths from the 25th or 75th percentiles.

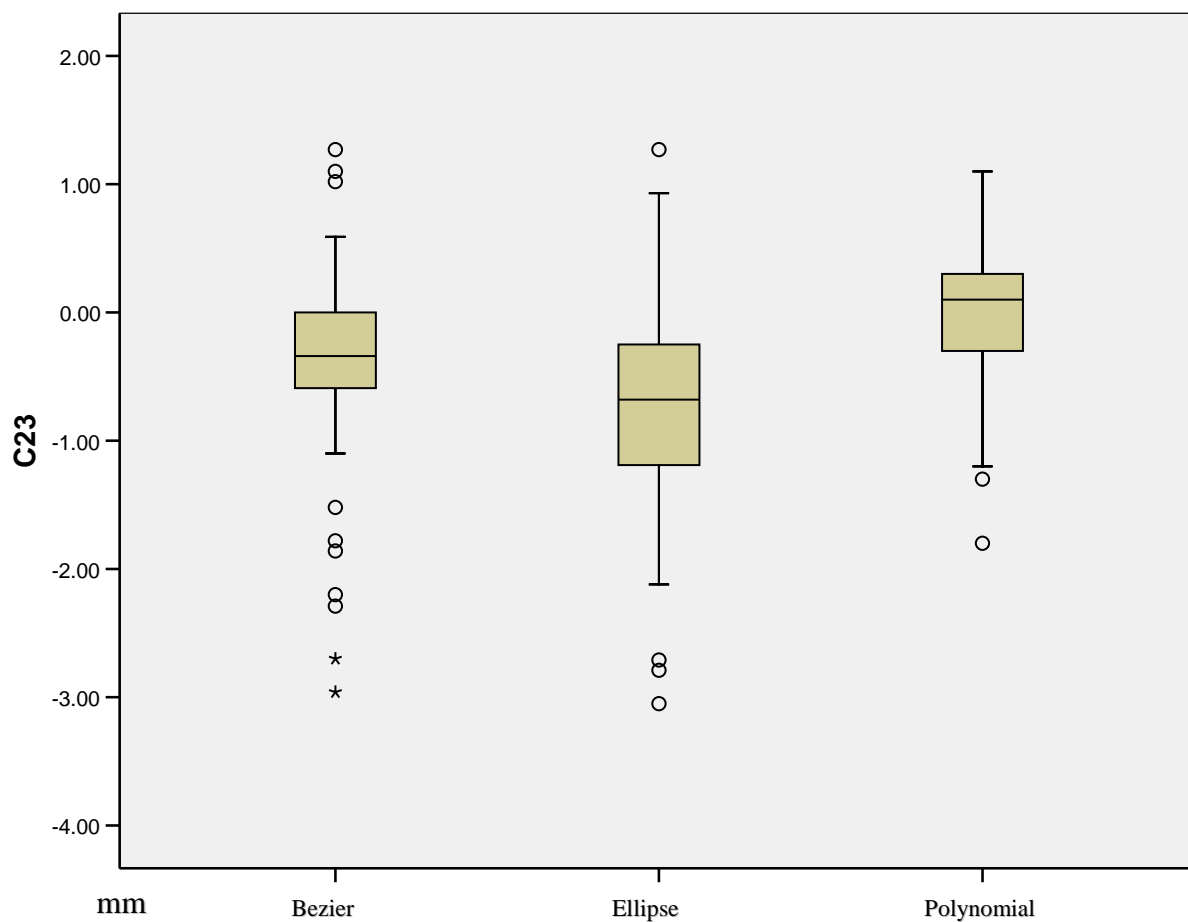


Figure 25: Box plot of tooth #23 for all three curves

Figure 25 shows that the Bezier curve has the most outliers for lower-left lateral incisor (tooth #23) lying within a range of -1.00 to -3.00, followed by the ellipse, and then the polynomial curve. The median of the polynomial curve is skewed to the positive.

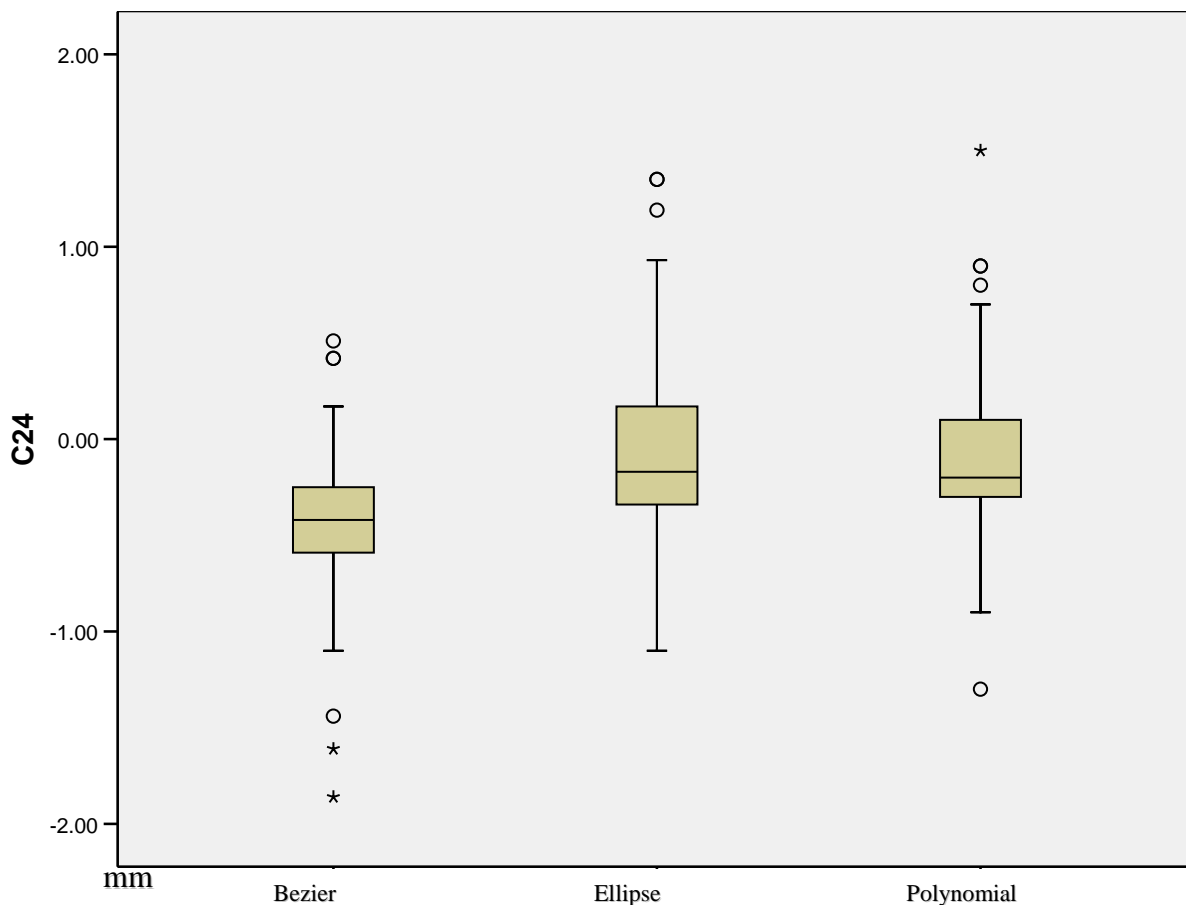


Figure 26: Box plot of tooth #24 for all three curves

Figure 26 shows that the Bezier curve has the most outliers for the lower-left central incisor (tooth #24) lying within a range of -1.00 to -2.00 and between 0.00 and 1.00. The ellipse's two outliers lie within 1.00 to 2.00. The polynomial curve has three outliers. One is between -1.00 to -2.00, and the other two lie within 0.00 to 1.00. The extreme value for the polynomial curve lies within 1.00 to 2.00. The medians for both the Bezier and polynomial curves appear similar and skewed toward the negative.

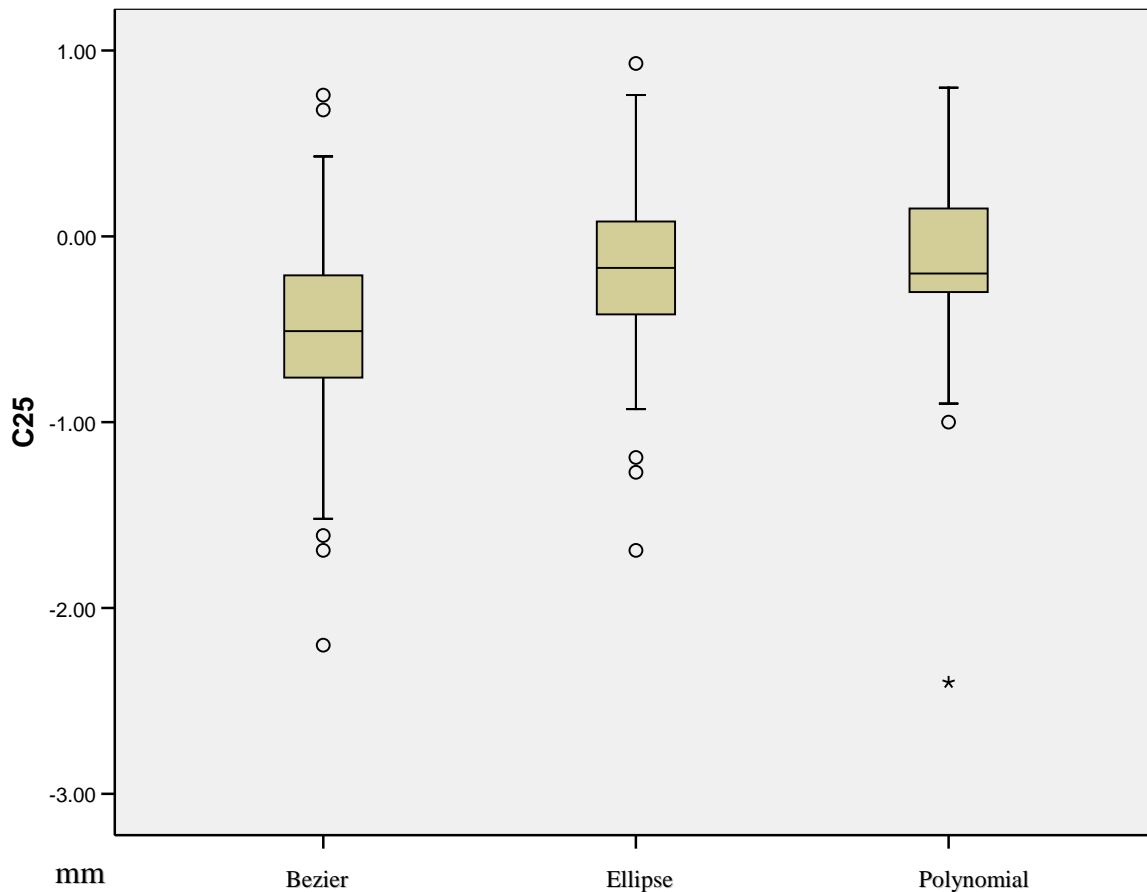


Figure 27: Box plot of tooth #25 for all three curves

Figure 27 shows that the Bezier curve has the most outliers for the lower-right central incisor (tooth #25) lying between -1.50 to -2.50 and 0.00 to 1.00. The ellipse has three outliers lying within -1.00 to -2.00 and a fourth outlier lying close to 1.00. The polynomial curve has one outlier close to -1.00 and one extreme value between -2.00 and -3.00. The median of the polynomial curve is quite skewed toward the negative.

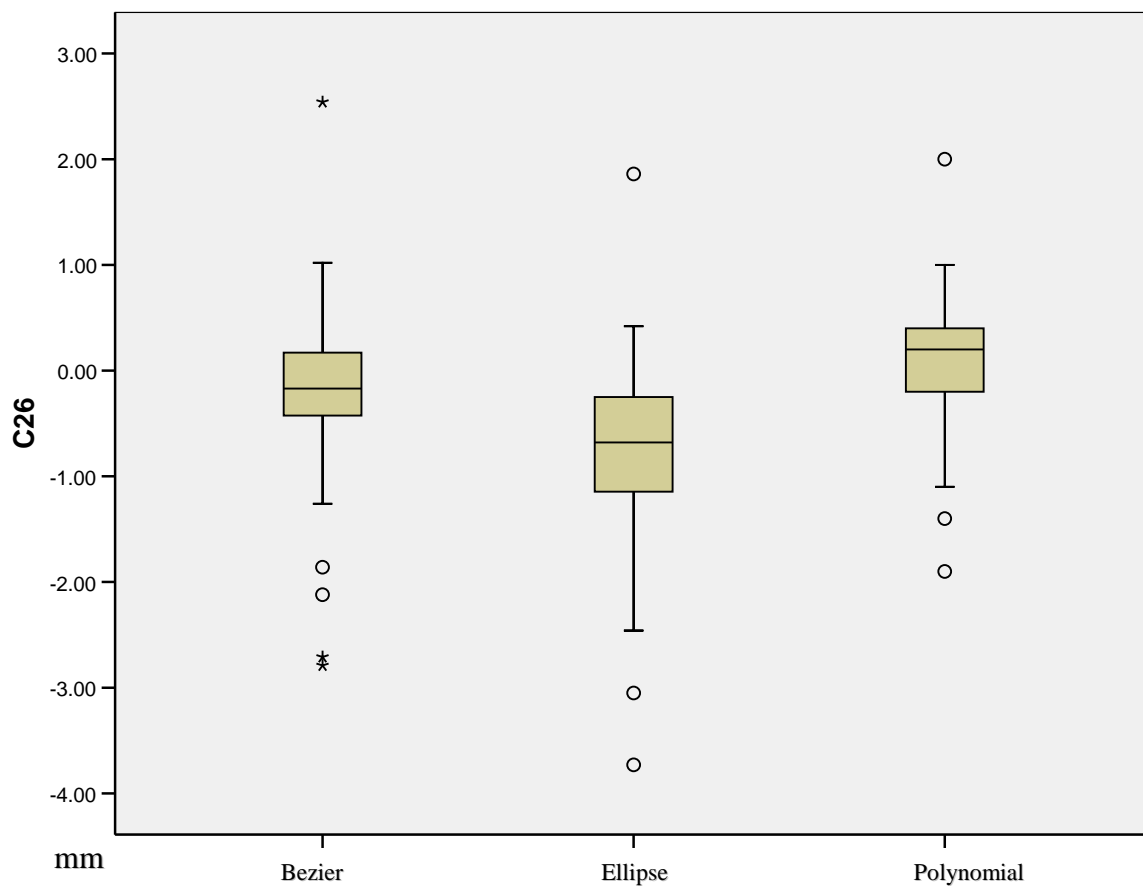


Figure 28: Box plot of tooth #26 for all three curves

Figure 28 shows that the Bezier has two outliers for the lower right lateral incisor (tooth #26) close to -2.00. Two of its three extreme values lie within -2.00 to -3.00, and the third outlier is between 2.00 to 3.00. The ellipse curve has two outliers lying within -3.00 to -4.00, and the third outlier lies between 1.00 and 2.00. The polynomial curve has two outliers between -2.00 and -3.00 and one outlier at 2.00. The median of the Bezier is slightly skewed toward the negative, and the polynomial curve is skewed positively.

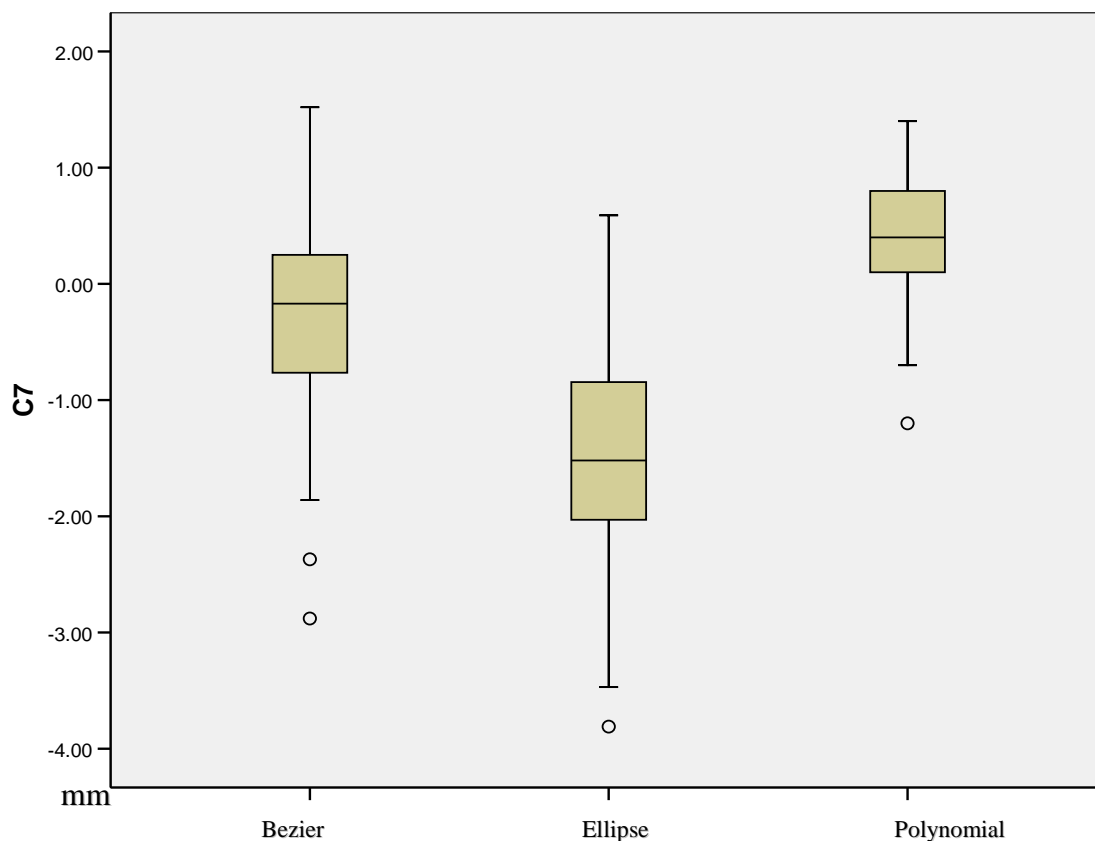


Figure 29: Box plot of tooth #7 for all three curves

Figure 29 shows that the Bezier curve has the most outliers for the upper-right lateral incisor (tooth #7) lying within a range of -2.00 to -3.00. The medians of all three curves are significantly spread apart. The median of the Bezier curve is slightly skewed toward the positive. The medians of the ellipse and polynomial curves are skewed toward the negative, even though the polynomial quartiles remain in the positive range.

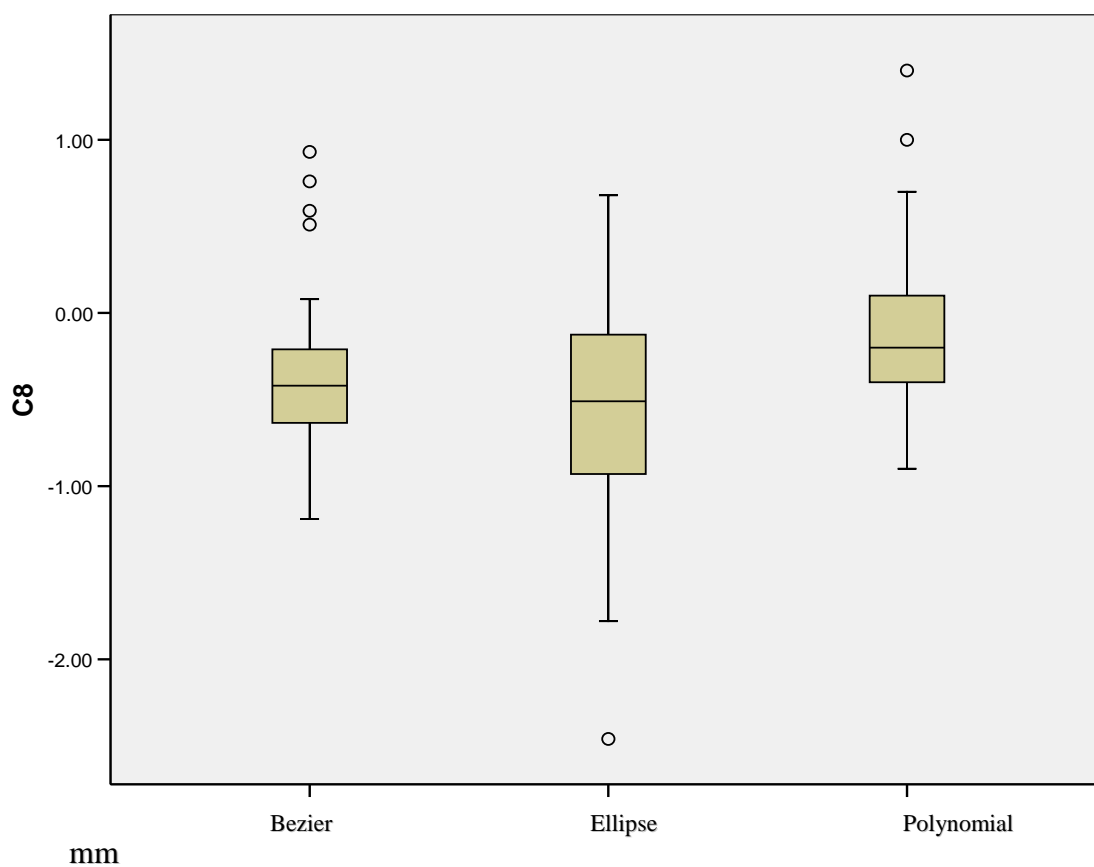


Figure 30: Box plot of tooth #8 for all three curves

Figure 30 shows that the Bezier curve has the most outliers for the upper-right central incisor (tooth #8) lying within a range of 0.00 to 1.00. The ellipse has one outlier greater than -2.00. The polynomial curve has two outliers between 1.00 and 2.00. The median of the polynomial curve is slightly skewed toward the negative.

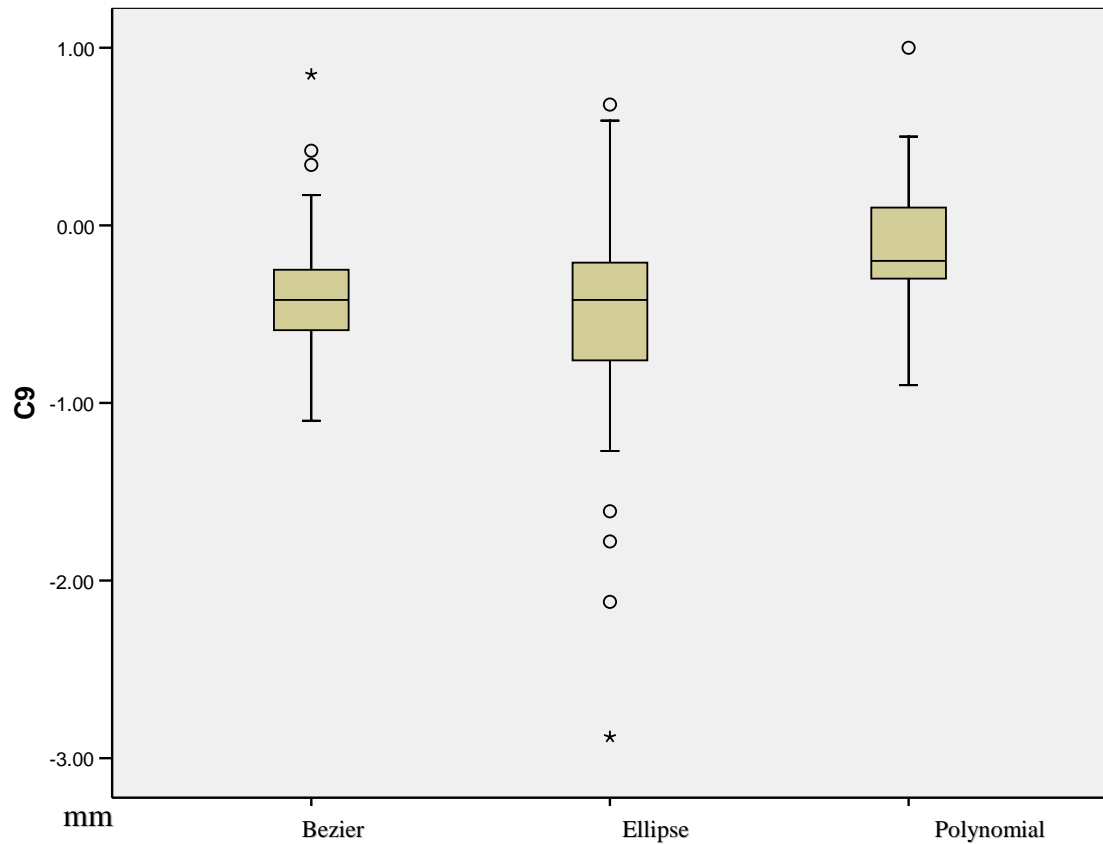


Figure 31: Box plot of tooth #9 for all three curves

Figure 31 shows that the ellipse curve has three outliers for the upper-left central incisor (tooth #9) lying within a range of -1.50 to -2.50 and one outlier between 0.00 and 1.00. It has an extreme value between -2.00 and -3.00. The Bezier curve has two outliers lying within 0.00 and 1.00 and an extreme value close to 1.00. The polynomial curve has one outlier at 1.00 and its median is skewed toward the negative.

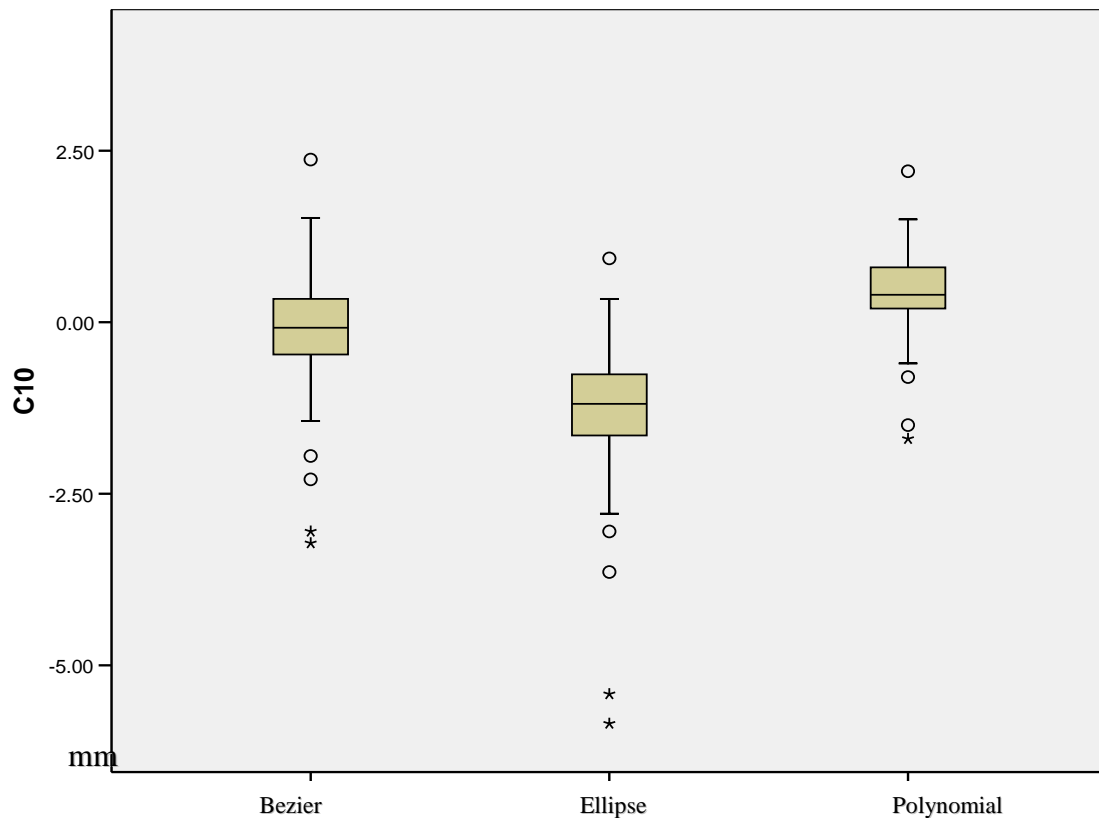


Figure 32: Box plot of tooth #10 for all three curves

Figure 32 shows that the all three curves have equal numbers of outliers. The Bezier curve has two outliers for the upper-left lateral incisor (tooth #10) lying within a range of 0.00 to -2.50 and one outlier close to 2.50. Its two extreme values lie within the range of -2.50 and -5.00. The ellipse has two outliers between 0.00 to -2.50, and one outlier lies between 0.00 to 2.50. Its extreme value lies within the 0.00 to -2.50 range and its median is skewed toward the negative even though the central box lies in the positive numbers.

The amount of variability for the distance of each tooth from each line was determined with the average variance being reported in Table 4.

CURVE	Tooth 7	Tooth 8	Tooth 9	Tooth 10	Tooth 23	Tooth 24	Tooth 25	Tooth 26	Avg.
Bezier	0.757	0.159	0.101	0.816	0.545	0.161	0.233	0.545	0.415
Ellipse	0.887	0.384	0.325	1.096	0.616	0.240	0.202	0.684	0.554
Polynomial	0.290	0.189	0.124	0.394	0.260	0.196	0.211	0.298	0.245

Table 4: Significant differences between curves are highlighted in yellow. Measurements are represented in mm.

The ellipse curve had the highest average variance of 0.554 mm in seven of the eight individual teeth. The Bezier curve had the second lowest average variance at 0.415 mm and the lowest variance for three of the eight teeth. The polynomial curve had the lowest average variance for the eight teeth at 0.245 and the lowest variance for four of the eight individual teeth. For teeth numbered 7, 10, 23 and 26, the variance for the polynomial curve was statistically and significantly lower than either the ellipse or the Bezier curves. The smallest variance is important in determining the best-fitting curve.

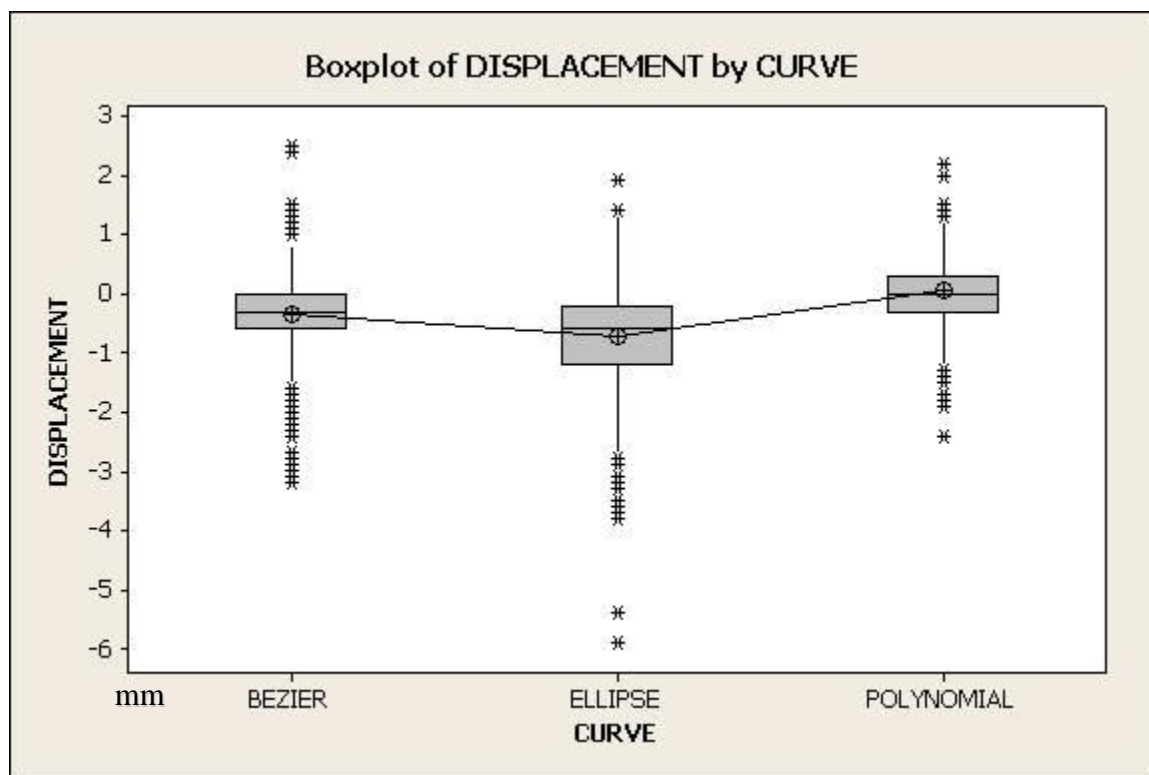


Figure 33: Box plot of displacement for all three curves

Figure 33 displays the results for displacement of the teeth for the Bezier, ellipse and polynomial curves. The shaded boxes represent the 25th - 75th percentiles. The horizontal line in the box is the median. The “whiskers” extend to the smallest and largest values that are not outliers. The outliers (asterisks beyond the whiskers) are 1.5 - 3 box lengths from the 25th or 75th percentiles. The sample size for the data displayed in the box plot is 1800 center points. The displacement measurements of the teeth are given on the left side of the graph. Figure 33 shows that the ellipse curve has more variability than the polynomial and Bezier curves. The outliers for both the Bezier and polynomial curves have larger values than the ellipse curve. The extreme outliers for the ellipse curve are prominent (in a range of -5.00 to -6.00) when measurements are negative compared to the other two curves.

The individual value plot of displacement versus the curve is a visual representation of the individual center points for displacement for each of the three curves to assess and compare sample distributions by plotting individual values for each variable. This makes it easier to spot outliers and visualize the distribution shape. Each dot in the following figure represents a value observed in the sample (dispersion), and the blue symbol on each plot represents the mean of the sample.

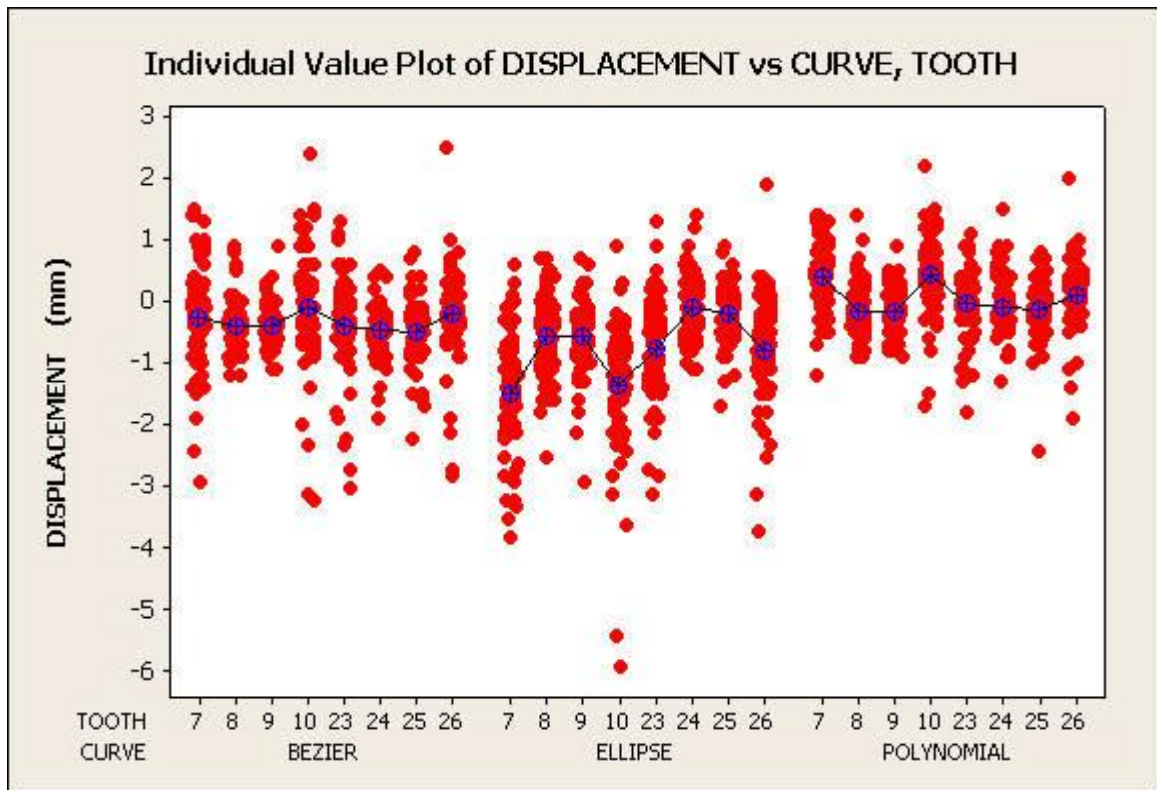


Figure 34: Dispersment of displacement values for all three curves

The following is a visual histogram of the center points for each tooth that examines the shape and spread of the sample data in this study. The histogram divides the sample values into many intervals called “bins.” The bars represent the number of observations falling within each bin (frequency distribution). The mean of this histogram is skewed to the left or to the negative.

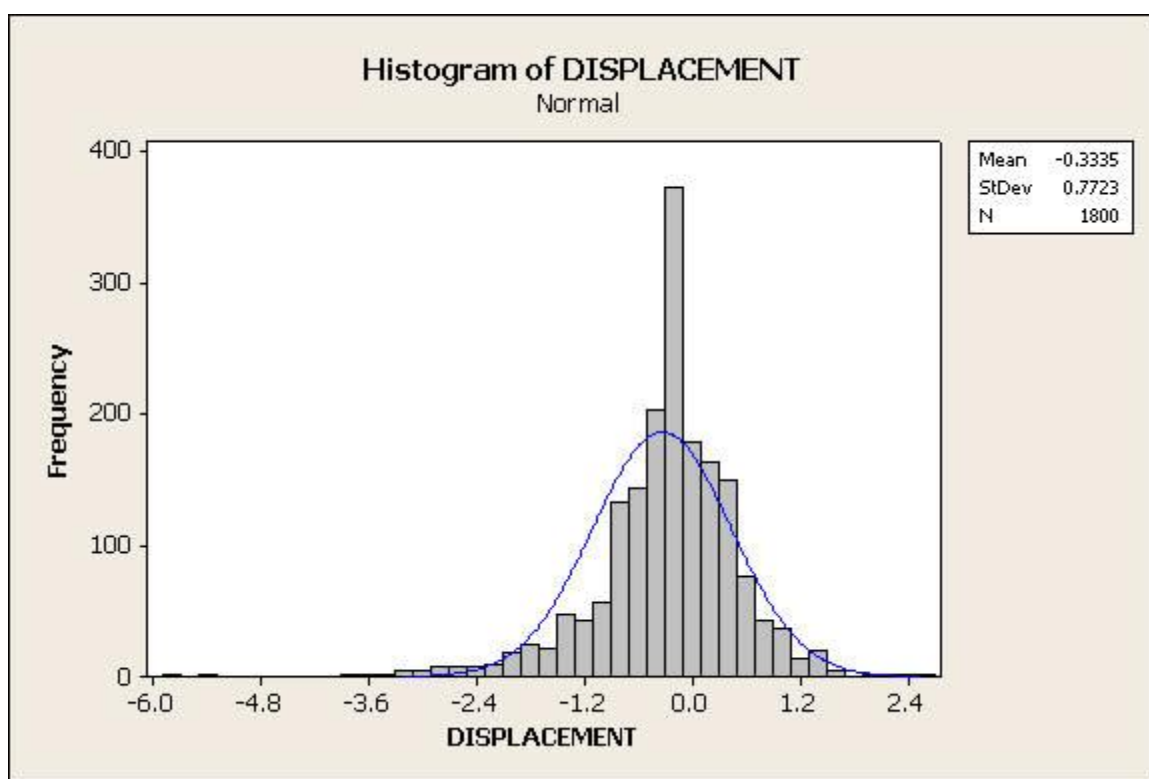


Figure 35: Histogram of displacement measurements for the center points of all the teeth studied

Table 5 (below) displays the results of the repeated measures “Analysis of Variance” (ANOVA) for the center points of each tooth. An ANOVA is commonly employed when comparing the effects of different factors between different groups of examiners. Wilks’ Lambda is one of four principal multivariate statistics used for testing the null hypothesis in repeated measures ANOVA. It is also referred to as the maximum likelihood criterion or U Statistic. This tests whether there are differences between the means of identified groups of subjects based on a combination of dependent variables. Wilks’ Lambda values closer to zero denote high discrimination between groups, where zero is a “great difference” and one is of “little difference.” The $F(2, 73)$ in Table 5 tests the multivariate effect of linear, independent, pair-wise comparisons among estimated marginal means.

Tooth	Wilks’ Lambda	$F(2, 73)$	p -value
C7	0.098	334.550	<.001
C8	0.632	21.268	<.001
C9	0.682	17.033	<.001
C10	0.120	266.657	<.001
C23	0.243	113.907	<.001
C24	0.489	38.154	<.001
C25	0.524	33.208	<.001
C26	0.210	137.044	<.001

Table 5: Multivariate results from repeated measures analysis of variance for the center points of each tooth.

Post-hoc testing is required following a significant repeated measures ANOVA result to determine specific differences among the equation displacement measurements.

The results of the post-hoc tests are shown in the following.

Tooth	Bezier	Ellipse	Polynomial	Post-Hoc
	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	
C7	-.254 (.8642)	-1.492 (.9357)	.404 (.5376)	B≠E≠P
C8	-.388 (.3958)	-.554 (.6159)	-.141 (.4322)	P≠B,E
C9	-.371 (.3162)	-.5387 (.5665)	-.168 (.3476)	B≠E≠P
C10	-.092 (.8988)	-1.3437 (1.0414)	.440 (.6260)	B≠E≠P
C23	-.374 (.7530)	-.732 (.7818)	-.020 (.5157)	B≠E≠P
C24	-.459 (.3992)	-.077 (.5009)	-.085 (.4498)	B≠E,P
C25	-.498 (.4992)	-.199 (.4486)	-.130 (.4590)	B≠E,P
C26	-.200 (.7337)	-.784 (.8237)	.120 (.5460)	B≠E≠P

Table 6: The mean, standard deviation and post-hoc results for displacement for each tooth.

Note: B = Bezier, E = ellipse, P = polynomial

The post-hoc test is a statistical test of mean difference performed after the tests for the main effects have been performed. Most often, the post-hoc test analyzes the differences among all possible combinations of groups, and in this case, whether the curves are different from each other. Table 6 shows the mean value of displacement for

the center points of each of the teeth studied for the Bezier, ellipse and polynomial curves. It is basically a table of differences. There is a significant difference between all three curves for teeth #7, #9, #10, #23 and #26. For tooth #8, there is a significant difference between the polynomial and the Bezier curves but less significant difference between the Bezier and ellipse curves. For teeth #24 and #25, there are significant differences between the Bezier and ellipse curves but less significant differences between the ellipse and polynomial curves. The mean for teeth #7, #10 and #26 appears to be positive, which indicates it goes to one side. The smallest standard deviation for each curve determines the best-fit curve for that tooth. Table 6 shows that the polynomial curve is the best-fit curve for teeth #7, #10, #23 and #26. The Bezier curve is the best-fit curve for teeth #8, #9 and #24, and the ellipse curve is the best-fit curve for tooth #25. Thus statistically overall, the polynomial curve represents the best-fit curve for the eight anterior teeth in this study.

Data Summary

1. Of the three curves, the polynomial curve had the lowest average of variance.
2. Of the three curves, the polynomial curve had the lowest sum of the absolute value of displacement from the curve.
3. The polynomial curve is the best-fitting curve based on the variance for measuring displacement of the eight anterior teeth.

Discussion

With the statistical results presented in this descriptive study of tooth displacement in the human dentition, it is important to explore the reliability and validity of the challenges, strengths and future direction for this forensic research. Recognizing the shortcomings as well as the value of this research will allow for better experimentation in future research efforts.

The Challenges in This Research

Establishing a baseline standard for displacement of the eight anterior teeth by using computer algorithms involved challenges in using the appropriate curve, suitable materials for scanning the exemplars and limitations of the measuring tool as well as the sample studied.

- Using the Appropriate Curve

Whether the Bezier, ellipse and polynomial curves make a difference in measuring displacement of the anterior teeth is indeed a valid question. The polynomial curve required all ten points to be created. The more points used in the curve-generation program, the smoother the curve. However, the polynomial curve did not have the same start and end points as those in the Bezier curve. The polynomial end point was located either inside or outside the center point of the opposite canine. An ellipse curve can be created with a minimum of two points, but in this study, it required four points to be created. There may be other mathematical parabolas worthy of investigating for a “fit” with the natural curve of an individual’s dentition. Even though some curves only needed a minimum of three points to be generated, missing teeth in a dental pattern caused problems due to key missing points needed for the generation of the curve for that

particular dentition. As reported in Table 4, the smallest average of variance determined the best-fit curve in this sample population. Statistically, four of the eight anterior teeth had variances that preferred a curve other than the polynomial as its best-fit choice. Future research is needed to address the independence of the curve to the anterior teeth utilized in this study.

The objective of establishing the best-fit curve was to minimize the distance of the tooth from the curve. However, since all individuals are unique, it may be unrealistic to expect an exact or one-size-fits-all curve for the human dentition. Statistically, the data showed that the Bezier curve is very similar in its results to the polynomial curve; however, the Bezier measurements are harder to replicate because of the subjective nature involved in the manual adjustments necessary to make the curve visually a best-fit for each individual arch. The Bezier curve has a start and end point at the canines and two control points on the anterior teeth that can be used to move the curve up (labial) or down (lingual). Utilizing a Bezier curve without any adjustments placed the curve inside (lingual) the anterior teeth every time. Since the Bezier measurements will vary with their adjustments, the data and statistical results will also change because the visual placement of the curve is dependent on the operator's perception of the best-fit curve for that individual arch. The ellipse and polynomial curves had no subjective manipulations, and thus more standardization was achieved. Given the reliability of digital imaging techniques and potential future discovery of an ideal parabolic equation, it may eventually be possible to develop an objective methodology that involves no individual adjustments in the development of a best-fit curve to quantify displacement of the anterior teeth.

- Materials for Scanning

The Surgident Coprwax™ provided satisfactory images of the bite imprints because of its color and clarity of detail. It is a valuable three-dimensional adjunct to dental casts and two-dimensional photographs.²⁴⁵ However, the possible distortion of these wafers must be considered since they were softened in a heated water bath and the biting force was individual for each volunteer. Moyco Beauty Wax™ has been used in other quantitative studies of bite marks and warms to a uniform softness (melting temperature ~66 degrees F) due to the presence of thermally conductive fillers. It resists distortion, is easy to manipulate and suitable for photography.²⁴⁶ It may be a better alternative than the Coprwax™. Continual use of the scanner in this study created a warm surface that could have affected the clarity of detail had the exemplars not been allowed to cool down for a brief time period between scanning exemplars. Other dental materials should be evaluated specifically for scanning purposes. Research has already begun on evaluating the biomedical factors of bite marks in cadavers. Scientific studies are needed to address fundamental aspects of bite mark analysis, specifically analysis of distortion of a bite in human skin.²⁴⁷

²⁴⁵ Johnson, "The Suspect," 419.

²⁴⁶ P. Nambier, T.E. Bridges and K.A. Brown, "Quantitative Forensic Evaluation of the Bite Marks with the Aid of a Shape Analysis Computer Program," Journal of Forensic Odontostomatology 13:2 (1995): 18-32.

²⁴⁷ Mary Bush et al., "Biomechanical Factors in Human Dermal Bite Marks in a Cadaver Model," Journal of Forensic Science 54:1 (January 2009):167-176.

- The Measuring Tool

The Adobe Photoshop[®] software—the forensic industry standard—is accessible and easy to use for anyone with basic computer knowledge. This tool allows the user to adjust the magnification level while maintaining the accuracy of the measurements. The measuring tool in Adobe Photoshop[®] measured the tooth at a 90 degree angle to the curve. The 90 degree method was utilized because it is very important for allowing replication by the users. Attempting to measure displacement manually without the aid of Photoshop's measuring tool would affect the precision of the measurement and affect the reliability of the methodology. The precision of the measurements in this study were limited to 0.1 mm/pixel by the resolution of the scanned image of the exemplars at 300dpi. Tooth displacement measurements from a bite imprint of a suspect or victim can be verified or duplicated by the dental forensic specialist or any computer specialist familiar with this software program.

- Study Limitations/Parameters

The following study limitations must be noted: (1) the dental imprints studied must have canine teeth in order to generate the three digital curves; (2) there can be no missing anterior teeth in order for the software program to create the curves digitally from designated crosshairs; (3) the exemplars used in this study were from the dental imprints of a population of only male volunteers 18 to 44 years of age; (4) there was no analysis of individuals of different races and ethnicities. Female volunteers were excluded due to the makeup of the convenience sample because four out of five rapes/sexual assaults against female victims have been committed by male perpetrators

(80%).²⁴⁸ With this U. S. government statistic, the male gender group is more likely to commit criminal acts that may involve bite marks.

The Strengths in This Research

The strengths in this research are its methodology in quantifying displacement from the center points of the teeth, its recognition of the significance of displacement in criminal investigations, and its potential in following in DNA's footsteps with regards to reliability and validity. Greater scientific benefits will be realized in determining the merits and methodology of defining displacement of the anterior teeth in the human dentition. Each of these strengths is described in the following.

- Measuring from the Center Points

The center points, not the mesial and distal points of the anterior teeth, were utilized to measure displacement to the three curves in this study. Displacement can be described using the concept of an instantaneous center of rotation.²⁴⁹ In orthodontics, the relationship between the force and the displacement of a tooth pattern has been studied extensively. A number of methods have studied the center of rotation in tooth movement and their relationship to force. Based on mathematical modeling and extrapolation from experimental studies, the force through the center of resistance on a single-rooted tooth of parabolic shape lies 0.4 mm distance from the alveolar crest to the apex.²⁵⁰ Small differences in the moment-to-force ratio can move the center of rotation from the apex to

²⁴⁸ <http://bjs.ojp.usdoj.gov> (Last visited March 2010). This data is from the Bureau of Justice Statistics' National Crime Victimization Survey (NCVS) 1993-2008. It includes estimates of the extent of crimes against females and the characteristics of crimes and victims.

²⁴⁹ C.J. Burstone, *Biomechanics of Tooth Movement in Vistas in Orthodontics*, Kraus, BS and RA Riedel, Editors, Philadelphia, PA: Lea & Febiger (1962): 197.

²⁵⁰ Louis A. Norton and Charles J. Burstone, *The Biology of Tooth Movement* (Boca Raton, FL: CRC Press 1989).

infinity to the incisal edge. Using the center point of an anterior tooth to record measurements to a mathematical curve is not subjective but rather objective. Since a tooth rotates on its axis, its rotation may not affect its positional relationship to its arch form or individual curve. Thus, the center point of the incisal edge is the most significant point for measuring a tooth's displacement from a mathematical curve that can be statistically quantified in the human dentition.

- The Significance of Displacement in Criminal Investigations

Forensic evidence is offered to support conclusions about individualization or classification of a source. In scientific terms, laboratory-based disciplines such as DNA analysis maintain a notable edge over disciplines based on expert interpretation, such as bite mark comparisons. There is, however, a clear link between the severity of a bite injury and its forensic significance. A greater number of dental characteristics of teeth that can be observed, measured and compared can increase the forensic significance and value of the dental evidence at trial. Conversely, a bite mark with few tooth characteristics would be regarded as having low forensic significance. Displacement of the anterior teeth can be one of those unique and measurable characteristics that would have an impact on the bite mark's forensic significance. A bite mark resulting in neither non-discrete bruising nor loss of tissue and severe tearing is usually made up of discrete factors such as small abrasions, individual bruises and visible lacerations. The bite marks in the middle of these extremes present the highest level of significance for bite mark analysis that will enable the exclusion and inclusion of potential suspects.

Dental forensic scientists have the background knowledge and experience to visualize and analyze the individual's arch form and locate the position of the anterior

teeth to determine whether the teeth fall inside (lingual), outside (labial), or exactly on the natural curve of the upper (maxillary) or lower (mandibular) arch. They can visually recognize unique aspects of an individual's tooth displacement from bite marks or dental imprints in other materials without microscopic analysis. To lay persons, however, the visual concept of tooth displacement may not present itself to be as apparent or understandable unless it is quite obvious (e.g., a tooth protruding as a "fang"). The present study describes in understandable terms the displacement of eight anterior teeth in the human dentition using three mathematical curves. When measuring displacement, the location of the tooth in relation to the curve is a critical component of recognition and recording algorithms by dental forensic scientists. It is, therefore, very important for experts to educate the trier of fact as to the descriptive elements from this research of displacement of teeth in a bite mark as potential evidence.

Human bite marks on skin are difficult to analyze by morphometric methods, especially when lateral movement of the dentition occurred during biting.²⁵¹ The skin is a substrate that constitutes a poor impression material and increases the likelihood of subjective conclusions by dental forensic scientists in our courtrooms. In 2007, researchers conducted a study to determine the amount and quality of DNA captured by a bite impression wafer and any inaccuracies in the impression technique to aid in identifying missing or abducted children.²⁵² According to the Federal Bureau of Investigation, the typical amount of DNA sought for analysis is 0.001 μ g, but samples of

²⁵¹ Bruce R. Rothwell, "Bite Marks in Forensic Dentistry: A Review of Legal, Scientific Issues" *JADA* 126 (February 1995): 223-232.

²⁵² Mark A. Ellis et al., "An Evaluation of DNA Yield, DNA Quality and Bite Registration from a Dental Impression Wafer." *JADA* 138:9 (2007): 1234-1240.

0.0002 μg can be typed.²⁵³ This study yielded an average of 0.0279 μg DNA isolated from the dental impression samples²⁵⁴ analyzed and thus can yield enough DNA for analysis. Currently, the reliability of DNA trumps the outcomes of bite mark analysis. Thus, the utility of taking dental impressions is demonstrated by the fact that two independent and complementary approaches to future identification are supported. The tooth displacement methodology of the present study can be combined with mitochondrial DNA (or *mtDNA*) analysis from the bite imprint, thus enhancing an investigation of a suspect or victim involved in a crime.²⁵⁵

It is important to note that when DNA is not present, as is sometimes the case in bite mark cases, the methodology to quantify displacement of the anterior teeth can stand on its own and be combined with other tooth characteristics and measurements. Because the displacement approach uses mathematical equations for the curves, it is independent, impartial and objective. The math functions serve as the control in this model because the arch curve never changes. Taken together, measurement of displacement of the anterior teeth from a curve and the analysis of other bite mark variables can provide information that would place possible biters at the scene of a crime. This is analogous to creating a differential diagnosis in medicine. It provides a basis for the next steps in reaching a conclusion as to whom the bite mark belongs.

DNA testing is a procedure that not all entities can afford to pursue or which cannot always be done, depending on the dental evidence. Thus, traditional measures will need to remain an integral component in forensic science. Whether DNA is present

²⁵³ Id.

²⁵⁴ Id.

²⁵⁵ *mtDNA* is the genetic material synthesized in the mitochondria of a cell.

and yet unable to be analyzed, or just not found due to outside elements, bite mark identification will continue to be extremely useful when dental characteristics such as anterior tooth displacement are universally defined. Traditional judicial processes generally consist of combining witness testimony, personal effects and clothing, anthropological and dental data to corroborate or to exclude the identity of an individual.²⁵⁶ Standardized, quantitative measurements of tooth variables are valuable information for providing evidence consistent with the identification of an individual from a limited number of implicated suspects involved in a crime.

- Following in the Footsteps of DNA Analysis

The less subjective the analysis in forensic science, the more useful the tool becomes to answer the questions of who, what, why, where, when and perhaps, how in courts of law. DNA analysis has been the ideal process for dental forensic scientists to copy and replicate the analyses of other evidence disciplines. DNA analysis has set the bar high for meeting reliability and validity standards.

Mitochondrial DNA (*mtDNA*) has become a powerful tool in forensic analysis for criminal investigations. The DNA in each of our genomes serves a variety of functions. Some of the DNA consists of specific genes that become enzymes and other proteins. Other sections of DNA are inactive and do not code for any functional proteins. These non-coding sections of DNA are of particular interest and importance in DNA identity testing. The sections of DNA that do not code for critical enzymes and other functional proteins have the ability to mutate and change without causing any physical or

²⁵⁶ J.P. Baraybar, "When DNA is Not Available, Can We Still Identify People?" Journal of Forensic Science 53:3 (May 2008): 533-540.

physiological consequences. These DNA sections allow forensic researchers to differentiate between individuals. Distributed through the human genome are small blocks of DNA (two to six nucleotides in length) called “Short Tandem Repeats” or STRs. STR loci are characterized by the number of repeated nucleotide blocks present in a sample. It is the STRs that are the current focus of forensic analysis methods. These STRs are used as the dependable DNA markers in human identification and animal pedigree registries such as the American Kennel Club and the Jockey Club.²⁵⁷

Human identification testing utilizes as a standard 13 STR markers with an additional eight STR loci available for analysis. Seven RFLP (Restriction Fragment Length Polymorphism) loci can also be used in complex forensic cases. Population statistics for these genetic loci are used in calculations of genetic profile frequencies and parentage statistics. One allele is donated to a person by the mother and another by the father, producing a mixture of both parents’ genetic codes.²⁵⁸

There are 46 chromosomes in the nucleus of every human cell and hundreds of thousands of mitochondria outside the nucleus but yet inside the cell. Each mitochondrion contains DNA that is 16,000 base pairs long and contains 37 genes. In contrast, nuclear DNA has 3.2 billion base pairs and approximately 40,000 genes. Only the *mtDNA* from a person’s mother is found in the cells in the human body. If one looks back six generations, it can be demonstrated that the nuclear DNA was inherited from 32 men and 32 women, and yet the *mtDNA* came from only one of those 32 women. This

²⁵⁷ DNA Identity Laboratory, “Short Tandem Repeats/Mitochondrial DNA.” www.hsc.unt.edu/departments/pathology (last visited March 2010).

²⁵⁸ *Id.*

makes *mtDNA* an ideal piece of genetic information to study relationships of human population groups throughout the world.²⁵⁹

Data obtained through the analysis of DNA represent the most objective evidence used in criminal investigations. The probability of DNA evidence from a biter, based on the relative rarity of the genotype in the population, and interpretation of DNA typing tests should be included with collateral tests of other evidence from a given case.²⁶⁰

Although the approach to quantifying displacement of the anterior teeth does not constitute the overall picture for a complete and definitive analysis of bite marks, it is a model for beginning to quantify human tooth variables in a consistent and objective way similar to the principles of *mtDNA*.

When individual tooth characteristics are first defined and then measured using the industry-standard imaging software program (e.g., Adobe Photoshop[®]), the methodology in bite mark analysis becomes less subjective. The ability to quantify displacement in the anterior teeth is foundational work for development of an alternative method to define dental characteristics in a manner similar to the 13 loci determinants in *mtDNA*. Numerous comparative computer-generated analyses have been done on bite mark overlays in efforts to evaluate error rates among examiners and assess the reliability of the techniques.²⁶¹

²⁵⁹ *Id.*

²⁶⁰ David Sweet, "Bitemarks as Biological Evidence" *Bitemark Evidence*, 192.

²⁶¹ Iain Pretty and David Sweet, "Digital Bite Mark Overlays-An Analysis of Effectiveness." *Journal of Forensic Sciences* (March 2001): 1385-1391. See also David Sweet and C. Michael Bowers, "Accuracy of Bite Mark Overlays: A Comparison of Five Common Methods to Produce Exemplars from a Suspect's Dentition." *Journal of Forensic Science* 43:2 (1998): 362-367. Anne McNamee et al., "A Comparative Reliability Analysis of Computer-Generated Bitemark Overlays," 400-405.

Interestingly, when these overlay techniques were compared, some dental examiners clearly defined each individual tooth and others simply followed the curvature of the teeth to produce a general outline of the arch.²⁶² Though the results of the bite mark overlay comparisons were fairly reliable between examiners, the lack of familiarity with all of the application features of Adobe Photoshop[®] software contributed to the variability and lack of objectivity in determining tooth position.²⁶³ Experience resulting from the present study suggests that providing any examiner, regardless of expertise, with clearly defined instructions to measure displacement of the anterior teeth will result in reliable and replicable data. Thus, even when DNA is present, tooth displacement methodology will function as a useful and significant adjunct in bite mark investigations.

The Future Direction of This Research

Dental forensic research has value in the forward direction it is headed. Despite a host of obstacles within the forensic community, research involving displacement of the anterior teeth has the ability to provide a more complete population study, affect the courtroom's view of dental forensic science and expand upon future studies and the advances needed in digital technology. Further research may also receive monetary and intellectual support in the near future from a government-sponsored forensic agency established to ensure reliability and validity of best practices among its dental forensic experts.

²⁶² Anne McNamee et al., "A Comparative Reliability Analysis of Computer-Generated Bitemark Overlays," 400-405.

²⁶² Id.

- A Complete Population Study

This study involved a data set of adult male exemplars (ages 18-33) because of their high incidence to commit crimes implicated with bite mark evidence. The research on male perpetrators is complicated by inconsistent or imprecise definitions of perpetrators and classifications of male perpetrators.²⁶⁴ Female victims have inflicted dental imprint patterns on their perpetrators and at some point, the displacement of their anterior teeth from dental imprints should be quantified using the same methodology used in this study. An equal number of female to male volunteers would support a more normal population sample of human dentitions in future studies. Seeking data from female bite marks would also enhance biological research in other areas of forensic science, such as DNA mapping and oral bacteria swabs.

- Bacterial Analysis Combined with Displacement

Studies are currently being conducted to examine the genotypes within the streptococci bacteria taken from a bite imprint. Bite marks are a source of DNA from the intact oral epithelial cells left behind, but they are not always recovered successfully—even under controlled laboratory conditions. In one study, female victims of sexual assault sought medical attention within 12 hours of an incident and there existed an opportunity to recover oral bacteria from evidentiary bite marks.²⁶⁵ Specifically, the oral bacteria of the genus *Streptococcus* was recovered in large numbers for up to 24 hours

²⁶⁴ Gail Shusterman and John Fluke, “Male perpetrators of Child Maltreatment: Findings from NCANDS” (2005) <http://www.aspe.hhs.gov>. (Last visited March 2010).

²⁶⁵ J.F. Peipert and L.R. Domagalski, “Epidemiology of Adolescent Sexual Assault,” *Obstetrics Gynecology* 84 (1994): 867-871.

from experimental bite marks inflicted on human skin.²⁶⁶ This same study found eight genomic ‘fingerprints’ of bacteria that could be matched exclusively to isolates recovered from the teeth of the biter.

Two years later, a technique was developed using an “Arbitrarily Primed Polymerase Chain Reaction” (AP-PCR) to allow detection of a greater number of oral bacteria to identify the perpetrator of a bite mark and to assess the natural distribution of oral streptococcal genotypes even after a 12-month period.²⁶⁷ This represents yet another valuable methodology in the analysis of bite mark evidence where DNA cannot be recovered. Combined with the results of a biter’s bacterial analysis and the quantitative values of displacement of the anterior teeth of a bite mark, this would provide substantial evidence linking a suspect to a crime.

- The Courtroom’s View: Need to Eliminate Gray Areas

A 17 month-old baby named Deidre was found dead dressed in adult panties, a half slip, and her pajama top. Examination of her body revealed superficial tearing of her vagina, bruising around her anus, neck and head, abrasions near an eye and upper lip, and a bruise pattern on her left thigh. The dental forensic scientist concluded the bruise pattern on her thigh was from a human bite, and photographs were taken. The details of the bite mark indentations were not sufficient to establish the identity of a suspected killer at the time.²⁶⁸

²⁶⁶ L.M. Borgula et al., “Recovery of Oral Bacteria from Experimental Bite Marks,” Journal Forensic Odontostomatology 21 (2003): 23-30.

²⁶⁷ M. Rahimi et al., “Genotypic Comparison of Bacteria Recovered from Human Bite Marks and Teeth Using Arbitrarily Primed PCR,” Journal of Applied Microbiology 99 (2005): 1265-1270.

²⁶⁸ Adrian Gundelach, “Lawyer’s Reasoning and Scientific Proof: A Cautionary Tale in Forensic Odontology,” Journal of Forensic Odonto-Stomatology 7:2

Nine years later, a Royal Australian Air Force serviceman named Carroll was under suspicion for breaking into the airwomen's quarters on base, leaving behind photographs of the airwomen dressed in only their underwear. Also found at the scene were the airwomen's undergarments with the crotch and nipple areas cut out as well as Carroll's thumbprint on one of the photographs.²⁶⁹

This deviant behavior manifested similarities found at the crime scene of the strangled baby, Deidre. Carroll's family home was in the immediate vicinity where Deidre's body was found. Carroll agreed to have dental impressions taken, and dental casts were made for analysis. These dental casts revealed that Carroll's upper jaw was V-shaped and his lower jaw was square. He had two large, distal-incisal synthetic fillings on his upper central incisors.²⁷⁰ Carroll claimed he was nowhere near his hometown at the time of the baby's death. Of equal interest, Carroll's ex-wife explained to police that the reason she left her husband was his abusive actions toward their 13 month-old baby girl. On occasion, he would bite his daughter's thighs. The ex-wife also said that during her pregnancy, Carroll told her if the baby were a girl, he wanted to name her Deidre.²⁷¹ In addition, the airmen serving with Carroll were suspicious of Carroll, recalling his absence three days prior to the date of the baby's murder. This could have given him ample time to travel to his hometown and return to base.²⁷²

Between the time of the baby's murder and when Carroll's dental impressions were taken, the Air Force dental records showed that Carroll had repairs made to his

(December 1989): 12.

²⁶⁹ Id.

²⁷⁰ Id.

²⁷¹ Id.

²⁷² Id at 13.

upper central incisors that were composite restorations. The dental forensic expert removed the incisal fillings in the working dental cast of Carroll's teeth to simulate the condition of his teeth prior to his dental work on base. Using photographs and a microscope²⁷³, three internationally respected dental forensic experts testified at Carroll's trial that he was the biter of the baby's thigh. Twelve years after baby Deidre was found strangled, Carroll was convicted by a jury for her murder.

Carroll later won an appeal because areas of disagreement existed among the opinions of the three dental forensic experts who testified. Two of the experts associated the upper bite pattern with all four upper incisors, and the third expert associated it with only three upper teeth. The same opinion was given for the lower bite pattern as well. Two of the experts stated the bite mark was made from the incisal edges whereas the third expert stated the bruise pattern was from the palatal edges of the teeth. There were no real differences between the three experts' general approach to define the biting edges of Carroll's teeth as they used the same reference points to make comparisons consistent with the photographs and their tracings. It was the small, superficial points of difference between the dental forensic experts that raised questions of doubt.²⁷⁴

This case demonstrated that there can be a considerable gap between scientific conclusions of dental forensic experts and the acceptance by others who are truly lay people when it comes to forensic science.²⁷⁵ The lesson here is that unless bite mark analysis results are totally unanimous among dental forensic experts at trial, judges and

²⁷³ Id.

²⁷⁴ Id at 16.

²⁷⁵ Id.

jurors may not accept them.²⁷⁶ Therefore if unanimity is to be the standard for admissibility, then scientific methodologies need to be uniform and less gray in the analyses of bite mark evidence.

This lesson remains true today. Small discrepancies in bite mark analyses are not unusual, even if all experts used the same methodology, protocol and instruments to make measurements of bite imprints. It requires substantial amounts of time and burdensome court costs to dispute expert testimony. Realistically, there is a greater chance that most dental forensic experts will disagree, and thus, the likely outcome is that the court will exclude the bite mark evidence. The simple reality is that the interpretation of dental forensic evidence is not always based on scientific studies to determine validity.²⁷⁷

The advent of *mtDNA* testing has changed the way our court system views dental forensic experts and their testimony. Since it is ultimately up to a jury to decide the credibility of dental forensic experts, it is important for these experts to use a foundational model as demonstrated in this study for the quantification of displacement in the anterior teeth. This has the potential to force dental forensic experts into expressing their bite mark analysis through a standardized lens. Currently, there is no universally accepted means of describing bite injuries, and hence, communication between professionals dealing with such injuries is complicated.²⁷⁸ By offering quantitative methodologies that are understandable to judges, juries, police officers, social workers

²⁷⁶ *Id.*

²⁷⁷ National Research Council of the National Academies, "Strengthening Forensic Science in the United States: A Path Forward," (Washington, D.C.: National Academies Press, 2009).

²⁷⁸ Iain A. Pretty, "Development and Validation of a Human Bitemark Severity and Significance Scale," *Journal of Forensic Sciences* (May 2007): 687-691.

and lawyers, the subjectivity in the gray areas of bite mark analyses would no longer be so vastly scrutinized. It is also necessary in the future to establish better partnerships between forensic scientists, law schools and legal scholars to provide sufficient training and background in scientific methodologies in dental forensics.

- Additional Studies

The courts of years past had accepted the tools and methodologies of forensic experts linking two indistinguishable marks produced by a single object and comparing matches to non-matches of evidence; rarely were their testimonies excluded. These experts assumed uniqueness to the exclusion of all others in the world. Today's lawyers continue to challenge speculative claims made by dental forensic experts. Without discernible uniqueness assumptions, dental forensic experts are compelled not only to develop population data on frequencies of variations in attributes and tests for independence but also to take measurements of variables in order to support their assumptions.²⁷⁹ Aside from this descriptive research, studies emphasizing tooth displacement today have only focused on the biomechanical perspective in orthodontics.

An interesting paper involving tooth displacement was a 2008 Purdue study that examined a 3-D method to calculate a coordinate system for each tooth and to assess the variation and accuracy. The researcher, a mechanical engineering student, used two digitally reconstructed dental casts and made comparisons before and after orthodontic treatment. The dental arch was defined from an imported software program called ProE[®]. Displacement of the left canine, left second premolar, and left first, second, and

²⁷⁹ Saks and Koehler, "The Coming Paradigm Shift in Forensic Identification Science," 892.

third molar were calculated.²⁸⁰ The Purdue 3-D methodology, however, failed to state how the dental arch was defined. The researcher subjectively imported the arch into a software program to place it in the correct occlusal plane and provided no details as to what it looked like or how it was configured originally.

The Purdue study did not quantify the displacement of the anterior teeth but only measured the coordinates of posterior teeth in a 3-D format. It was developed for orthodontics, but it could be applied to the dental forensic sciences, specifically to bite mark analysis. Since only two dental casts comprised the sample size, it would need a power analysis to establish a larger sample size to determine important statistical significance. And lastly, the Purdue study would not be able to stand up to the rigorous scrutiny of our judicial system in order to gain credibility in dental forensic sciences. Though 3-D computer technologies represent an area of current interest in forensic comparison analyses of bite marks, the Purdue study and others lack the basic foundations in measurements of the dental bite mark variables. The usability of this method may have forensic application for future research, but it will depend on the accuracy and adaptability of the software program.

The coordinate methodology of the posterior teeth proposed in the Purdue study to quantify displacement is intriguing because of its 3-D digital reconstruction capabilities. It utilized software that may have the potential to quantify individual teeth in the analysis of bite mark imprints in various substrates including human skin. The method behind Purdue's technology appears far less difficult to replicate than the Kieser

²⁸⁰ Jie Chen Shuning Li, "Quantification of Tooth Displacement from Dental Casts," paper presented at the Summer Bioengineering Conference for the American Society of Mechanical Engineering, Marco Island, FL, 2008, 25-29 June 2008.

study²⁸¹ focusing on the geometric and morphometric analysis to determine the uniqueness of the human anterior dentition.

In 2007, Kieser and his fellow researchers analyzed 33 maxillas and 49 mandibles from post-operative orthodontic dental casts of young individuals ages 17-20 of both sexes to determine the uniqueness of the anterior teeth.²⁸² Kieser argues that dental forensic experts typically rely on measurements of selected distances, angles or ratios between subjectively identified landmarks and that his use of digital imaging has facilitated the location of landmarks as coordinates.²⁸³ Two landmark and two “semi-landmark” dots were placed on the incisal edges of the anterior teeth to capture the geometry of morphological shape of the teeth on a three-dimensional deformation grid (Figure 36).

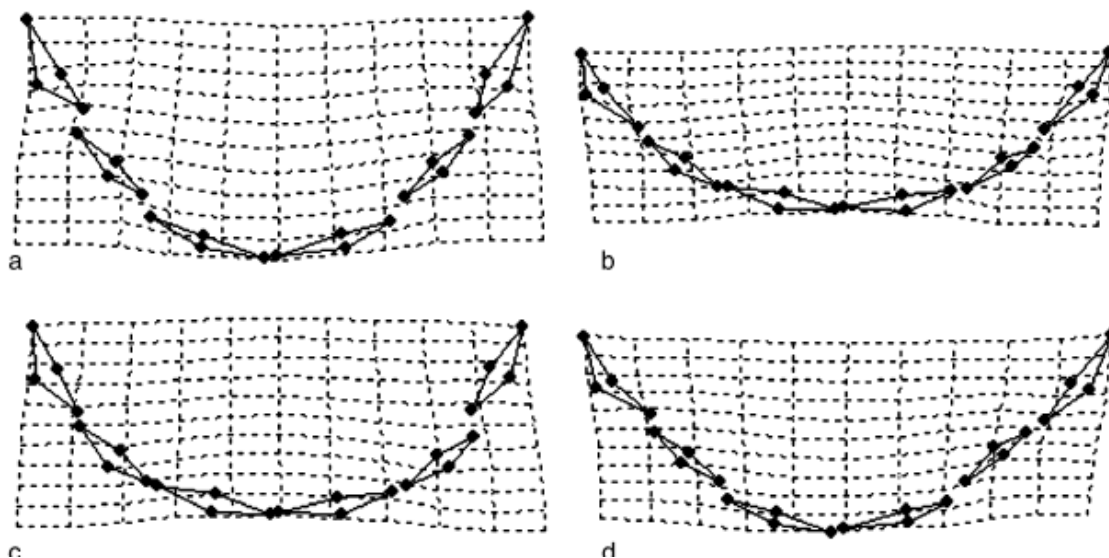


Figure 36. Kieser's geometric morphological analysis on a deformation grid shows individual arch curves. (Courtesy of Jules Kieser.)

²⁸¹ Jules A. Kieser et al., “The Uniqueness of the Human Anterior Dentition: A Geometric Morphometric Analysis,” *Journal of Forensic Science* 52: 3 (May 2007): 671.

²⁸¹ Id.

²⁸² Id.

Kieser's methodology was quite extensive involving a sophisticated array of digital techniques in its evaluation of coordinates. These involved a new family of geometrical morphometric methods and relative warp analysis (RW). Geometrical morphometry is the mathematical definition of shape and size.²⁸⁴ This study addressed the issue of individuality of the anterior teeth and created interesting arch forms or curves. However, no attempt was made to evaluate how these surfaces might create an individual's bite pattern either in wax or on skin.²⁸⁵ It is the quantification of the displacement feature in the anterior teeth that must set the standard for further approaches for defining the individuality of dental characteristics in the human bite mark. More rigorous protocols are needed to validate basic premises and techniques of matching dental characteristics within larger population studies.

- Advances in Digital Technology

Simplifying the placement of the crosshairs on both ends of each anterior tooth and allowing the best software program to record all of the measurements automatically would help to standardize the process in the present study and minimize error rates. Adobe Photoshop[®] is the popular program used to select the biting surfaces of anterior teeth and to produce the many bite mark overlays for analyses.²⁸⁶ Improving the Photoshop[®] measuring tool to allow the closest measurement from the anterior tooth's center point without the operator's subjective input would improve the accuracy of the statistical data. It would contribute to the uniqueness of the bite mark if Photoshop[®]

²⁸⁴ Id. at 672.

²⁸⁵ Id. at 676.

²⁸⁶ Raymond J. Johansen and C. Michael Bowers, "Digital Analysis of Bite Mark Evidence," *Forensic Odontology* 45:2 (April 2001): 327-342.

measurements recorded several decimal points beyond a tenth of a millimeter.

Photoshop[®] states that the precision of the measurements is dependent on the resolution of the image used.²⁸⁷

In 2007, DentalPrint[®] software was studied to determine if its automatic procedures are comparatively better than Adobe Photoshop[®] software in analyzing bite marks. Freshly slaughtered piglets were used as subjects to compare the bite marks created from 17 dental casts. The dental casts exhibited variations in the presence, status and arrangement of the upper and lower anterior teeth.²⁸⁸ The objective of the piglet study was to determine values of intra- and inter-examiner reliability, sensitivity, specificity and validity for the new DentalPrint[®] software program.²⁸⁹ DentalPrint[®] may be capable of measuring displacement of the anterior teeth with the click of a mouse. This would eliminate a step in the process to make accurate measurements of displacement to the curve in this study.

The piglet study documented the use of DentalPrint[®] as an accurate forensic technique for dental forensic experts to identify correctly the human dentition belonging to a particular bite. In recent years, the judicial system has expressed dissatisfaction with bite mark evidence because of the subjective nature of its comparative analyses and an insufficient body of published work that defines the statistical parameters of the procedures that form the basis of scientific conclusions.²⁹⁰ The DentalPrint[®] (3-D)

²⁸⁷ George Reis, Photoshop[®] CS3 for Forensic Professionals, (Indianapolis, IN: Wiley Publishing, Inc. 2007): 161.

²⁸⁸ Stella Martin-de las Heras et al., "Effectiveness of Comparison Overlays Generated with DentalPrint[®] Software in Bite Mark Analysis," Journal of Forensic Science 52:1 (January 2007): 151.

²⁸⁹ Id.

²⁹⁰ David Sweet and IA Pretty, "A Look at Forensic Dentistry-Part 2: Teeth as

software has the potential to refine the computer-based methods of image processing for use in bite mark analysis needed by our courts.²⁹¹ Yet as the *Swinton* court explained, the courts need to understand a difference between *presenting* evidence and *creating* evidence and not let that distinction be blurred.²⁹²

Regardless of the sophistication of digital technology software programs used to improve the validity of bite mark analyses, the foundational aspect to quantify dental characteristics to establish the uniqueness of a “numerical personal identifier” needs to be accomplished first. It would be beneficial to utilize advancing orthodontic methodologies used to achieve a perfectly aligned dentition and assess the positional movement involving displacement of the anterior teeth in bite mark imprints. Bite mark recognition could then record and compare the spatial geometry of the human dentition’s distinctive characteristics such as displacement of teeth, tooth width, and restorations to current scanned imprints with a digitized reference template. Using the correct algorithm, these templates would not be reversible nor designed to generate originals; thus protecting privacy and employed to discriminate between bite marks in criminal investigations.

- Formation of NIFS

Advances in dental forensic sciences have demonstrated valuable assistance in successfully prosecuting and convicting criminals as well as exonerating innocent people. The development and federal funding of a newly formed, independent National Institute

Weapons of Violence-Identification of Bitemark Perpetrators,” British Dental Journal 190: 8 (April 28, 2001): 415-418.

²⁹¹ Martin-de las Heras, “Effectiveness of Comparison Overlays Generated with DentalPrint[®] Software in Bite Mark Analysis, 156.

²⁹² State v. Swinton, 2003 WL 235 15 279 (Conn.), 804.

of Forensic Science (NIFS) proposed in a January 2009 government report²⁹³ would promote an aggressive, long-term agenda to help strengthen all forensic science disciplines. This agency would be well-connected to the scientific research base in the U.S. to create meaningful advances in forensic science practices and methodologies that affect criminal and civil litigation, homeland security, natural disaster preparedness and advancement in forensic technologies.

More specifically in terms of reliability and validity, the NIFS would fund peer-reviewed research in several areas. First, it would promote studies establishing the scientific bases demonstrating the validity of forensic methods. Second, the NIFS would facilitate the development and establishment of quantifiable measures of the reliability and accuracy of forensic analyses. These studies would establish the limits of reliability and accuracy that analytic methods can be expected to achieve as the conditions of forensic evidence vary and would be peer-reviewed and published in respected scientific journals. Third, the NIFS would facilitate the development of quantifiable measures of uncertainty in the conclusions of forensic analyses. Lastly, the NIFS would facilitate the automated techniques capable of enhancing forensic technologies. With effective leadership, this entity would set the highest standards for sound forensic policies and provide adequate resources including national support for the forensic science system.²⁹⁴

²⁹³ National Research Council of the National Academies, “Strengthening Forensic Science in the United States: A Path Forward,” (Washington, D.C.: National Academies Press, 2009).

²⁹⁴ Id.

Conclusion

The significance of this research study is represented by the establishment of the parameters for the definition of displacement of eight anterior teeth in the human dentition. Displacement is a measurable dental variable that can be scientifically quantified to assist in identification of the individuality in a bite pattern or imprint from a victim and/or suspect(s). Because the teeth in the upper and lower jaws are shaped in an arch form, three mathematical curves were evaluated as guides to statistically quantify where teeth fall in relationship to their individual curve. The polynomial curve was shown to be the best choice of the three curves studied because it does not require complex curve-fitting algorithms and has the lowest statistical variance. It is also the most objective and accurate methodology of the three curves analyzed; thus it, allows for standardization and ease of usage in forensic dental sciences.

This study may lead to definitive approaches for analysis of bite marks that provide the necessary rigor required by the judicial process with regard to the scientific basis for objective interpretations of dental characteristics in the human dentition. Since *mtDNA* cannot always be recovered, additional valid scientific methodologies are needed to better identify dental tooth patterns within the forensic and judicial arenas. Yet, jurors are demanding expensive and often unnecessary DNA tests, handwriting analyses, gunshot residue testing, and other procedures that are not pertinent to the case.²⁹⁵ Because of the “CSI effect”²⁹⁶ the technology to determine an individual’s bite mark or dental pattern can have an impact on jurors as well. This in turn, may force both the

²⁹⁵ Jeffrey Heinrick, “Everyone’s an Expert: The CSI Effects’ Negative Impact on Juries” *The Triple Helix* (Arizona State University 2006): 59.

²⁹⁶ *Id.* The “CSI effect” is the perception of the near-infallibility of forensic science in response to the TV show.

defense and prosecution to present more scientifically sound and airtight cases, selectively choose more scientifically-educated jurors, or may become a permanent part of the courtroom dynamics.²⁹⁷

It is likely that the digital technology used in this research will be peer-reviewed to further its evidentiary benefit and usefulness in courtrooms. Authentication of bite mark evidence using Adobe Photoshop[®] and the Wirtz computer software program allowed for objective and repeatable measurements of displacement in dental imprints. This may only enhance the value of a human bite mark as being credible and definitive evidence. It must be stated that the polynomial measurement used in the present study is not perfect and can be improved. Research should continue to identify a better parabolic function that creates a smooth curve and requires no subjective adjustments such as those used for the polynomial curve in this study. The ideal methodology would utilize the canine-to-canine start and end points, and allow for missing teeth in the dental arch.

Despite the limitations in this study, dental displacement of the anterior teeth is established as a quantifiable dental variable for the individuality of the anterior teeth of the human dentition and enhances the unique properties of bite marks for analysis in future criminal investigations. Though some current bite mark comparisons use 3-D digital techniques and methodologies, the best-fit curve warrants evaluation to establish displacement of the anterior teeth in this format as well. Together with the partnership of dental forensic science and the law, this study can improve the relationship between the two and begin to settle concerns regarding the validity and reliability of dental forensic results.

²⁹⁷ Heinrick, "Everyone's an Expert: The CSI Effects' Negative Impact on Juries," 61.

BIBLIOGRAPHY

- Baraybar, J.P. "When DNA is Not Available, Can We Still Identify People?"
Journal of Forensic Science 53:3 (May 2008): 533-540.
- Barnett, P.D. Ethics in Forensic Science: Professional Standards for Practice of Criminalistics. Boca Raton, FL: CRC Press 2001.
- Barry, Larry A. "Bite Mark Evidence Collection in the United States."
Bulletin of the History of Dentistry 42:1 (March 1994): 21-26.
- Beech Aircraft Corp. v. Rainey, 488 U.S. 153, 169 (1988).
- Bernitz, Herman et al. "A Technique to Capture, Analyze, and Quantify Anterior Teeth Rotations for the Application in Court Cases Involving Tooth Marks."
J Forensic Science (May 2006): 624-629.
- Bernstein, Mark L. "Nature of Bitemarks," Bitemark Evidence,
(New York, NY: Marcel Dekker 2005): 59-80.
- Borgula, L.M et al. "Recovery of Oral Bacteria from Experimental Bite Marks."
Journal Forensic Odontostomatology 21 (2003): 23-30.
- Bowers, C. Michael. Forensic Dental Evidence. San Diego, CA: Elsevier Academic Press 2004.
- Bowers, C. Michael. "The Balance of DNA and Bite Marks: A Lawyer's Point of View."
Forensic Odontology (2000): 99-107.
- Burstone, C.J. "Biomechanics of Tooth Movement" in Vistas in Orthodontics.
Kraus, BS and RA Riedel, Editors, Philadelphia, PA: Lea & Febiger (1962): 197.
- Bush, Mary et al. "Biomechanical Factors in Human Dermal Bite Marks in a Cadaver Model."
Journal of Forensic Science 54:1 (January 2009): 167-176.
- Carmichael v. Samyang Tire Inc., 131 F. 3d 1433,1435. (S.D. Ala. 1996).
- Cheney, Ward and David Kincaid, Numerical Mathematics and Computing.
Pacific Grove, CA: 4th Edition (1999): 364.
- Clark, Steven C. et al. "Medicolegal Death Investigator."
Occupational Research and Assessment, Inc. (1996): 266-270.
- Cottone, James A. and S. Miles Standish. Outline of Forensic Dentistry.
Chicago, IL: Year Book Medical Publishers, Inc. (1982).

Dailey, J. Curtis. "Computer-Assisted Identification of Vietnam War Dental Remains." Military Medicine Journal (January 1995).

Daubert v. Merrell Dow Pharmaceuticals, Inc., 509 U.S. 579, 597 (1993).

Dinkel, E.H. Jr. "The Use of Bite Mark Evidence as an Investigative Aid." Journal of Forensic Science (November 1973): 535-547.

Dorion, Robert B.J. Bitemark Evidence. New York, NY: Marcel Dekker 2005.

Doyle v. State, 263 S.W. 2d 779 (1954).

DNA Identity Laboratory. "Short Tandem Repeats/Mitochondrial DNA," www.hsc.unt.edu/departments/pathology (last visited March 2010).

Ellis, Mark A. et al. "An Evaluation of DNA Yield, DNA Quality and Bite Registration from a Dental Impression Wafer." JADA 138:9 (2007): 1234-1240.

Faigman, David L. et al. Science in the Law: Forensic Science Issues. American Casebook Series. St. Paul, MN: West Group, 2006.

Faigman, David L. et al. Modern Scientific Evidence: Forensics. 2006 Student Edition Thomson West.

Faigman, David L. et al. Science in the Law: Standards, Statistics and Research Issues. American Casebook Series. St. Paul, MN: West Group, 2002.

"Federal Rules of Evidence 702 Advisory Committee Note 2000." Cornell University Law School, Legal Information Institute. (Last visited March 2010). <http://www.law.cornell.edu/rules/fre/ACRule702.htm>.

Fischman, S.L. "Bite marks." Alpha Omegan 95:4 (December 2002): 42046.

Frye v. United States, 293 F.1013, 1014 (D.C. Cir. 1923).

Furness, J. "Teeth Marks and their Significance in Cases of Homicide." Journal of the Forensic Science Society 9 (1969): 169.

General Electric Company v. Joiner, 522 U.S. 136, 146 (1997).

Giannelli, Paul C. "The Admissibility of Novel Scientific Evidence: Frye v. United States, Half-Century Later," 80 Colum. L. Rev. 1197, 1250 (1980).

Giannelli, Paul C. Understanding Evidence. Newark, NJ: LexisNexis 2003.

- Giannelli, Paul C. and Edward J. Imwinkelried, Bite Mark and Dental Identification, 3rd ed. (1999), 603.
- Gilbert v. California, 388 U.S. 263 (1967).
- Gold Standard. The American Heritage® Dictionary of the English Language. Fourth Edition. Houghton Mifflin Company, 2004.
- Graham, Michael H. “The Expert Witness Predicament: Determining ‘Reliable’ Under the Gatekeeping Test of Daubert, Kumho, and Proposed Amended Rule 702 of the Federal Rules of Evidence.” U. MIAMI LAW REV. 54 (2000): 317-321.
- Groffy, Ronald L., comp. Recognition, Preservation and Collection of Bite Mark Evidence. Wisconsin Department of Justice, Crime Laboratory Bureau, 3rd revision, January 1997.
- Gundelach, Adrian. “Lawyer’s Reasoning and Scientific Proof: A Cautionary Tale in Forensic Odontology.” Journal of Forensic Odonto-Stomatology 7:2 (December 1989): 10-16.
- Heller v. Shaw Industries, Inc., 167 F.3d 146, 160 (3d Cir. 1999).
- Heinrick, Jeffrey. “Everyone’s an Expert: The CSI Effects’ Negative Impact on Juries” The Triple Helix (Arizona State University 2006): 59.
- Hill, I.R. “Evidential Value of Bite Marks,” in Forensic Odontology (2000): 93-97.
- Huber, PE. Galileo’s Revenge: Junk Science in the Courtroom. BasicBooks 1991.
- Imman, K. and N. Rudin. “The Origin of Evidence.” Forensic Science International 126: 1 (2002): 11-16.
- Imwinkelried, Edward J. Evidentiary Foundation. Newark, NJ: LexisNexis, 6th ed. 2005.
- Wisconsin Innocence Project: R.L. Stinson, Evaluation of Bitemark Evidence (February 13, 2008).
- Johansen, Raymond J. and C. Michael Bowers. “Digital Analysis of Bite Mark Evidence.” Forensic Odontology 45:2 (April 2001): 327-342.
- Johnson, L. Thomas. “The Suspect.” Bitemark Evidence. New York, NY: Marcel Dekker (2005): 419.
- Johnson, L. Thomas and David Cadle. “Bite Mark Evidence: Recognition, Preservation, Analysis, and Courtroom Presentation.” New York State Dental Journal 55 (1989): 38-41.

- Johnson, L.T. et al. "Quantification of a Database of the Human Dentition: Methodology" Journal of Forensic Identification 58:4 (August 2008): 409-416.
- Kassirer, Jerome P. and Joe S. Cecil. "Inconsistency in Evidentiary Standards for Medical Testimony." JAMA 288:11 Reprinted (September 18, 2002): 1382-1387.
- Katz v. United States, 389 U.S. 347 (1967).
- Kieser, Jules A. et al. "The Uniqueness of the Human Anterior Dentition: A Geometric Morphometric Analysis." Journal of Forensic Science 52: 3 (May 2007): 671-677.
- Kitchens, Larry J. Exploring Statistics. St. Paul, MN: West Publishing Company (1987).
- Kumho Tire v. Carmichael, 526 U.S. 137 (1999).
- LaFave, Wayne R., Jerold H. Israel, Nancy J. King and Orin S. Kerr. Criminal Procedure. St. Paul, MN: West Publishing Company 5th Edition (2009).
- Leary, Mary G. "Proof of Identification of Bite Marks." American Jurisprudence 3rd Edition (October 2003).
- Leesfield, Ira. H. and Mark A Sylvester. "Admissibility of Expert Testimony: What's Next?" http://expertpages.com/news/admissibility_testimony.htm (Last visited March 2010).
- Lust v. Merrell Dow Pharmaceuticals, Inc., 89 F.3d 594, 598 (9th Cir. 1996).
- MacFarlane, T.W., D.G. MacDonald and D.A. Sutherland. "Statistical Problems in Dental Identification." Journal of Forensic Science 14 (1974): 247-252.
- Martin-de las Heras, Stella et al. "Effectiveness of Comparison Overlays Generated with DentalPrint[®] Software in Bite Mark Analysis." Journal of Forensic Science 52:1 (January 2007): 151-156.
- McCormick, Charles. McCormick's Evidence, 6th Edition Volumes 1 & 2 (1954).
- McNamee, Anne, David Sweet and Iain Pretty. "A Comparative Reliability Analysis of Computer-Generated Bitemark Overlays." Journal of Forensic Science 50:2 (March 2005): 400-405.
- Mincer, Richard A. and Harry H. Mincer. "Science and the Law," in Bitemark Evidence. New York, NY: Marcel Dekker (2005): 465-475.
- Miranda v. Arizona, 384 U.S. 436, 86 S. Ct. 1602, 16 L. Ed.2d 694 (1966).

- Murmann, Denise C. et al. "A Comparison of Animal Jaws and Bite Mark Patterns." Journal of Forensic Science 51:4 (July 2006): 846-860.
- Nambier, P., T.E. Bridges and K.A. Brown, "Quantitative Forensic Evaluation of the Bite Marks with the Aid of a Shape Analysis Computer Program," Journal of Forensic Odontostomatology 13:2(1995): 18-32.
- National Research Council of the National Academies. "Strengthening Forensic Science in the United States: A Path Forward". Washington, D.C.: National Academies Press, January 2009.
- "New Automated System IDs Victims of Mass Disasters in Minutes." November 2007. <http://www.rsna.org>, (Last visited March 2010).
- Nikaido, Akira et al. "A Dental Radiograph Registration Algorithm Using Phase-Based Image Matching for Human Identification," ISPACS 2006.
- Norton, Louis A. and Charles J. Burstone. The Biology of Tooth Movement. Boca Raton, FL: CRC Press 1989.
- Oregon v. Elstad, 470 U.S. 298, 105 S. Ct. 1285, 84 L. Ed.2d 222 (1985).
- Paoli R.R. Yard PCB Litigation, 35 F.3d 717, 744 (3d Cir. 1994).
- Peipert, J.F. and L.R. Domagalski. "Epidemiology of Adolescent Sexual Assault." Obstetrics Gynecology 84 (1994): 867-871.
- Pennsylvania v. Muniz, 496 U.S. 582 (1990).
- People v. Marx, 54 Cal. Appl 3d 100, 126 Cal. Rptr. 350, 77 A.L.R. 3d 1108 (2d Dist. 1975)
- People v. Milone, 43 Ill. App.3d 385, 2 Ill. Dec.63, 356 N.E. 2d 1350 (2d Dist. 1976).
- People v. Smith, 110 Misc 2d 118, 443 N.Y.S. 2d 551 (County Ct. 1981).
- Pitteway, M.L.V. "Algorithm for drawing ellipses or hyperbolae with a digital plotter." Computer Journal 10 (1967): 282-289.
- PostScript® Language Reference Manual, Adobe Systems Incorporated, Reading, MA: Addison-Wesley Publishing Company, 3rd Edition, 1999.
- Pretty, Iain A. "Unresolved Issues in Bitemark Analysis" in Bitemark Evidence, (New York, NY: Marcel Dekker 2005): 547-563.
- Pretty, Iain and David Sweet. "The Scientific Basis for Human Bitemark Analyses-Critical Review." Science & Justice 41:2(April/June 2001): 85-92.

- Pretty, Iain and David Sweet. "Digital Bite Mark Overlays-An Analysis of Effectiveness." Journal of Forensic Sciences (March 2001): 1385-1391.
- Pretty, Iain A. "Development and Validation of a Human Bitemark Severity and Significance Scale", Journal of Forensic Sciences (May 2007): 687-691.
- Rahimi, M et al. "Genotypic Comparison of Bacteria Recovered from Human Bite Marks and Teeth Using Arbitrarily Primed PCR." Journal of Applied Microbiology 99 (2005): 1265-1270.
- Rawson, R.D., R.K. Ommen and J.G. Kinnard. "Statistical Evidences for the Individuality of the Human Dentition." Journal of Forensic Science (January 1984): 245-253.
- Reis, George. Photoshop[®] CS3 for Forensic Professionals. Indianapolis, IN: Wiley Publishing, Inc. 2007: 161.
- Rochin v. California, 342 U.S. 165, 166 (1952).
- Rothwell, Bruce R. "Bite Marks in Forensic Dentistry: A Review of Legal, Scientific Issues" JADA 126 (February 1995): 223-232.
- Ruiz-Troche v. Pepsi Cola, 161 F.3d 77, 85 (1st Cir. 1998).
- Rutty, G.N., A. Abbas, and D. Crossling. "Could Earprint Identification Be Computerized? An Illustrated Proof of Concept Paper." International Journal of Legal Medicine 119 (2005): 335-343.
- Saks, Michael J. and Jonathan J. Koehler. "The Coming Paradigm Shift in Forensic Identification Science." Science Magazine 309 (August 5, 2005): 892-895.
- Schmerber v. California, 384 U.S. 757 (1966).
- Shusterman, Gail and John Fluke. "Male perpetrators of Child Maltreatment: Findings from NCANDS" (2005). <http://www.aspe.hhs.gov>. (Last visited March 2010).
- Shuning Li, Jie Chen. "Quantification of Tooth Displacement from Dental Casts." Paper presented at the Summer Bioengineering Conference for the American Society of Mechanical Engineering, Marco Island, FL, 2008, 25-29 June 2008.
- State v. Stinson, 397 Wis. 2d. 224, 397 N.W. 2d. 136 (Ct. App. 1986).
- State v. Swinton, 2003 WL 23515279 (Conn.).

- Stimson, Paul G. and Curtis A. Mertz. Forensic Dentistry Boca Raton, FL: CRC Press 1997.
- Sullivan, Robert. The Disappearance of Dr. Parkman. Boston, MA: Little, Brown, and Company (1971).
- Sweet, David. "Dental DNA Evidence." Forensic Odontology. Belgium: Leuven University Press (2000): 87-91.
- Sweet, David. "Human bite mark evidence" Forensic Odontology. Belgium: Leuven University Press (2000): 75-79.
- Sweet, David. "Bitemarks as Biological Evidence" Bitemark Evidence. New York, NY: Marcel Dekker (2005): 183-201.
- Sweet, David and C. Michael Bowers. "Accuracy of Bite Mark Overlays: A Comparison of Five Common Methods to Produce Exemplars from a Suspect's Dentition." Journal of Forensic Science 43:2 (1998): 362-367.
- Sweet, David and IA Pretty. "A Look at Forensic Dentistry-Part 2: Teeth as Weapons of Violence-Identification of Bitemark Perpetrators." British Dental Journal 190: 8 (April 28, 2001): 415-418.
- SWGIT. "Guidelines for the Use of Imaging Technologies in the Criminal Justice System." Guidelines for the Forensic Imaging Practitioner Version 2.3 (June 6, 2002); 1-7.
- Swokowski, Earl W. Calculus with Analytic Geometry. Boston, MA: Prindle, Weber & Schmidt, Inc. 3rd Edition (1984): 562.
- Swokowski, Earl W. Elementary Functions with Coordinate Geometry. Boston, MA: Prindle, Weber & Schmidt, Inc. (1971): 61.
- Thomson, Helen. Murder at Harvard. Boston, MA: Houghton Mifflin Company (1971).
- United States v. Dionisio, 410 U.S. 1 (1973).
- Vale, Gerald L. "History of Bitemark Evidence." Bitemark Evidence. New York, NY: Marcel Dekker (2005): 1-29.
- Wagner, Glenn N. Scientific Methods of Identification. Boca Raton, FL: CRC Press 1997.
- Willems, Guy. Forensic Odontology. Leuven, Belgium: Leuven University Press 2000.
- Winston v. Lee, 470 U.S. 753, 757 (1985).

Zarowski, P. "Bite Mark Evidence: Its Worth in the Eyes of the Expert."
J Law Ethics Dent 1:47 (1988).

WEB SOURCES

www.nlm.nih.gov/visibleproofs/galleries/technologies/virtopsy.html
(Last visited March 2010)

<http://portal.acm.org/citation.cfm?id=282943> (Last visited March 2010)

<http://bjs.ojp.usdoj.gov> (Last visited March 2010)

<http://mathdl.maa.org/mathDL/46/> (Last visited April 2010)

APPENDICES

Appendix A: Polynomial Formula

The following method was used to calculate the coefficients for the polynomial curve:

$$y = ax^2 + bx + c.$$

x=pixel location of row coordinate

y=pixel location of column coordinate

N=Sample Size – number of points used in calculation of coefficients

$$P = \text{Sum}(x)$$

$$Q = \text{Sum}(x^2)$$

$$R = \text{Sum}(x^3)$$

$$S = \text{Sum}(x^4)$$

$$T = \text{Sum}(y)$$

$$U = \text{Sum}(x * y)$$

$$V = \text{Sum}(x^2 * y)$$

$$W = N * Q * S + 2 * P * Q * R - Q^3 - P^2 * S - N * R^2$$

$$a = (N * Q * V + P * R * T + P * Q * U - Q^2 * T - P^2 * V - N * R * U) / W$$

$$b = (N * S * U + P * Q * V + Q * R * T - Q^2 * U - P * S * T - N * R * V) / W$$

$$c = (Q * S * T + Q * R * U + P * R * V - Q^2 * V - P * S * U - R^2 * T) / W$$

This automated method to calculate the coefficients is reported at
<http://www.eng-tips.com/viewthread.cfm?qid=55381>.

Appendix B: Ellipse Formula

The following method was used to generate a computer graphic ellipse curve. The Ellipse curve is based on three points:

pixcol1 is the central point of one cuspid either tooth #6 or tooth #22.

pixcol10 is the central point of cuspids tooth #11 or tooth #27.

pixrow 5 and pixrow 6 are the mesial points of anterior teeth either teeth #8 & #9 or teeth #24 & #25.

This first process transforms the points since maxillary images were marked from right to left.

```

IF pixcol1 > pixcol10
ex1 = pixcol10
ex2 = pixcol1
ey1 = INT(pixrow5+(pixrow6-pixrow5)/2)
baserow = INT(pixrow1 + (pixrow10-pixrow1)/2)
ey2 = baserow + abs(baserow - ey1)
ELSE
ex1 = pixcol1
ex2 = pixcol10
ey1 = INT(pixrow5+(pixrow6-pixrow5)/2)
baserow = INT(pixrow1 + (pixrow10-pixrow1)/2)
ey2 = baserow - abs(baserow - ey1)
ENDIF

```

```

a = abs(.5 * (ex2 - ex1))
b = ABS(.5 * (ey2 - ey1))
tinc = PI() * 2 / ( a + b)
centx = ((ex1 + ex2) + .5) * .5
centy = ((ey1 + ey2) + .5) * .5

```

```

Iterate from 0 to PI
FOR pnt = 0 + tinc TO PI() * 2 STEP tinc
Draw point of ellipse
Column = ROUND(centx + a * COS(pnt),0)
Row = ROUND(centy - b * SIN(pnt),0)
Endif

```

This automated method to generate an ellipse in computer graphics is adapted from a posting at <http://www.answers.com/topic/ellipse>.

Appendix C: IRB Approval

OFFICE OF RESEARCH COMPLIANCE



July 18, 2008

Maureen Otto
Children's Hospital of Wisconsin

Dear Ms. Otto:

This letter is in regard to Dr. L. Thomas Johnson's protocol #HR-1027 entitled, "*Data Base Generation on the Individuality of the Human Dentition.*" This protocol was originally expedited by the Marquette University Institutional Review Board on September 27, 2004, and received timely continuing review each year thereafter. In July 2007 Dr. Johnson and his research team completed data collection. Dr. Johnson notified the MU IRB that the study was closed for enrollment, and that he and his research team would begin data analysis of the de-identified data, with no further contact with the research participants.

The MU IRB approves of the continued data analysis beyond the last approval period ending September 26, 2007. The de-identified data analysis may continue indefinitely. Because the data analysis of a de-identified data set does not constitute engagement in human subjects research (45 CFR 46.102), Ms. Peggy Van Scotter-Asbach is approved to conduct data analysis of the data collected under MU IRB approved protocol #HR-1027.

Please contact Marquette's Office of Research Compliance at 414-288-1479 if you have any further questions. Thank you.

Sincerely,



Melissa J. Lauritch, J.D.
Research Compliance Officer