NIST Interagency Report
NIST IR 8352-DRAFT

Bitemark Analysis:
A NIST Scientific Foundation Review

Draft Stage

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Submit Comments

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Abstract

This report summarizes a review of the scientific foundations of bitemark analysis conducted by the National Institute of Standards and Technology (NIST). Bitemark analysis typically involves examining patterned injuries left on a victim or object at a crime scene, identifying those injuries as bitemarks, and comparing those marks with dental impressions from a person of interest. This review specifically focuses on pattern injuries found on human skin. Over 400 sources were considered via literature searches and input from previous efforts by the National Institute of Justice Forensic Technology Center of Excellence. Our NIST review also utilized input from an October 2019 Bitemark Thinkshop organized by the Center for Statistics and Applications in Forensic Evidence (CSAFE) where experts and stakeholders associated with bitemark analysis were convened to discuss key issues. Based on this input, our study found a lack of support for three key premises of the field: 1) human dentition is unique at the individual level, 2) this uniqueness can be accurately transferred to human skin, and 3) identifying characteristics can be accurately captured and interpreted by analysis techniques. Furthermore, our review noted a lack of consensus among practitioners on the interpretation of bitemark data as well as thoughts on how to move the field forward. If the field seeks to advance, the key takeaways provided in this review are starting points for areas needing improvement, not an exhaustive list of specific shortcomings.

Keywords

bitemark; forensic odontology; pattern evidence; dentition; dental morphology; forensic science; scientific foundation review; interpretation; transference; overlays.

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Preface

Forensic science plays a vital role in the criminal justice system by providing scientifically based information through the analysis of physical or digital evidence. The National Institute of Standards and Technology (NIST) is a non-regulatory scientific research agency within the U.S. Department of Commerce with a mission to advance measurement science, standards, and technology. NIST has been working to strengthen forensic science methods for almost a century. In recent years, several scientific advisory bodies have expressed the need for a review of the scientific bases of forensic methods and identified NIST as an appropriate agency for conducting such reviews. A scientific foundation review, also referred to as a technical merit evaluation, is a study that documents and assesses the foundations of a scientific discipline, that is, the trusted and established knowledge that supports and underpins the discipline's methods. Congress has appropriated funds for NIST to conduct scientific foundation reviews in forensic science. These reviews seek to answer the question: "What established scientific laws and principles as well as empirical data exist to support the methods that forensic science practitioners use to analyze evidence?" Background information on NIST scientific foundation reviews is available in NISTIR 8225 at https://doi.org/10.6028/NIST.IR.8225.

Acknowledgments

Richard Cavanagh and Willie May, who have both retired from NIST, provided valuable input on early efforts with this project. Lynn Garcia from the Texas Forensic Science Commission supplied input on their previous efforts to assess bitemark evidence. John Morgan, and later Heidi Eldridge and others, from RTI International provided access to a bitemark literature list they assembled as part of a separate review. The Center for Statistics and Applications in Forensic Evidence (CSAFE), a NIST Forensic Science Center of Excellence, organized an October 2019 Bitemark Thinkshop attended by almost 50 practitioners, researchers, statisticians, and other stakeholders. We gratefully acknowledge the attendees of this thinkshop and their contributions to the discussions held there. A summary of this thinkshop, written by Hal Stern and Alicia Carriquiry along with SNA International contractors, is available at https://www.nist.gov/forensic-science/scientific-foundation-review-bitemark-analysis. As with any field, the scientific process (research, results, publication, additional research, etc.) continues to lead to advancements and better understanding. Information contained in this report comes from the authors' technical and scientific perspectives and review of information available to us during the time of our study.

Glossary and Acronyms

AAFS: American Academy of Forensic Sciences

ABFO: American Board of Forensic Odontology

ASFO: American Society of Forensic Odontology

Bitemark: the pattern in a substance resulting from a bite (whether human or non-human). In food or wax, the pattern is more often visible as a result of indentations or impressions and occurs with sometimes little force from the biter (for example bitemarks left in wax or cheese). In skin, the pattern is seen as a vital response to the injury: through swelling, scraping (abrasion), bruising (contusion), or tearing (laceration) of the flesh. Depending on the force of the bite and the skin, the tissue may not show a response and therefore some bites may not leave a mark.

Bitemark Analysis: the examination of patterned marks left on a victim or object at a crime scene and comparing those marks with dental impressions from a person of interest.[1]

Class Characteristics: features or traits that distinguishes a bitemark from other pattern injuries or human dentition from non-human dentition patterns

Dental Abrasion: wear on teeth not caused by tooth-on-tooth contact

Dental Arch: arrangement or alignment of maxillary and/or mandibular teeth in the mouth

Dentition: the arrangement of the teeth in the maxillary and mandibular arches

Dental Prothesis: artificial replacement of one or more teeth and structures

Displacement: teeth displaced toward facial/lingual aspect

Forensic Odontology: the use of specialized knowledge in dentistry to assist investigative agencies

Foil: a dentition from an individual that is not a person of interest to be used as a distractor for bitemark data comparisons.

Individual Characteristics: features or traits that distinguish one person, or their teeth, from any other

IOFOS: International Organization for Forensic Odonto-Stomatology

NRC: National Research Council

Pattern Evidence: markings produced when one object acts upon another object; includes fingerprints, bitemarks, and toolmarks.

PCAST: President's Council of Advisors on Science and Technology

Position: location of tooth in the dental arch in relation to others

[1] This report acknowledges that a victim may bite a perpetrator in the course of the attack, however, this report focuses on bites left on a victim and the process to identify the biter.

Rotation: tooth is displaced along its longitudinal axis

Transference: the ability of an object to leave identifying characteristics in material it contacts

Wear Pattern: distinctive shape or form of wear on individual teeth

Executive Summary

All scientific methods have limits and one must understand these limits to use a method appropriately. This is especially important in forensic science as critical decisions impacting life and liberty are often based on the results of forensic analyses.

The American Board of Forensic Odontology (ABFO) defines a bitemark as a "physical alteration or representative pattern recorded in a medium caused by the contact of teeth of a human or animal." For human bitemarks, this pattern would demonstrate features, traits, or characteristics that distinguish the patterned injury as a bitemark (ABFO 2018). Bitemark analysis typically involves the examination of patterned injuries left on a victim or object at a crime scene, identification of those injuries as bitemarks, and comparison of those marks with dental impressions from a person of interest (POI).

The assumption that an individual can be identified from bitemarks left on human skin has, for several decades, seen a steady increase in scientific scrutiny. In 1960 following an experiment where multiple people left bitemarks in food items, a British dentist concluded "evidence which involves the identification of a person by tooth-marks left as bruises in flesh should never be admitted [in court], and evidence involving bitemarks in, for example, foodstuffs should be examined extremely critically" (Fearnhead 1960). Unlike the use of dental information to identify human remains, bitemarks are primarily made from only the anterior teeth and are prone to distortions due to bite force, location of the bite, and movement of the biter or victim during the biting event – all of which can lead to an innocent person not being excluded as the source of a bitemark.

This scientific foundation review examined the existing bitemark literature to answer two questions: 1) Can bitemarks be accurately associated with teeth that left them? and 2) What data exist to support or refute this claim in bitemark analysis? The aim of this foundation study is to promote a better appreciation of the capabilities and limitations of the practice within the forensic community as well as among other stakeholders, including investigators and legal professionals. Given the questions already arising from practitioners within this field about the legitimacy of the fundamental assumptions required to establish a verifiable source of a bitemark (Avon et al. 2010) and the frequency at which such claims are disproven with DNA testing (Bowers 2006), this review also focused on the limitations inherent to this practice and under what conditions they are being observed.

Obtaining input from experts outside of NIST is an integral component of a NIST scientific foundation review. As described in Chapter 3, the NIST team followed the process outlined in NISTIR 8225 for conducting this review. This involved:

- collecting and evaluating the peer-reviewed literature,
- assessing publicly available data from interlaboratory studies, proficiency tests, and laboratory validation studies,
- exploring other available information, including position statements and non-peer reviewed literature, and obtaining input from members of the relevant community

through interviews, workshops, working groups, and other formats for the open exchange of ideas and information.

In addition, this NIST review also sought community input from the 2019 CSAFE Thinkshop involving practitioners, stakeholders, and researchers. A conclusion from this workshop was that there is a critical need for research to explore the scientific foundations of bitemark analysis, including assessing the reliability and validity of determinations made as to bitemark type (human vs nonhuman vs not a bitemark) and in linking dentition to bitemarks.

It is noted that bitemark analysis represents only a portion of forensic dentistry (odontology) activities. Antemortem dental records, for example, involving the full human dentition, routinely enable postmortem identification of human remains. This review does not explore the whole discipline of forensics odontology; the focus is on bitemarks left on human skin.

Three primary postulates are important for successful bitemark analysis: (1) that dental characteristics, especially the arrangement of the anterior teeth, differ substantially among individuals (i.e., uniqueness), (2) skin or other marked surfaces can reliably capture those differences (i.e., transference), and (3) a bitemark examiner can reliably compare anterior dentition information with the bitemark image (i.e., interpretation) (Hale 1978, Pretty & Sweet 2001, Saks et al. 2016). This review considers each of these three postulates and finds limited data to support them. Therefore, the ability of bitemark analysis to accurately exclude or not exclude individuals as a source of the mark is not supported.

Key takeaways identified as part of this foundation study include the following (numbering is based on their sequence within the chapter where they are derived):

KEY TAKEAWAY #1.1: Forensic bitemark analysis lacks a sufficient scientific foundation because the three key premises of the field are not supported by the data. First, human anterior dental patterns have not been shown to be unique at the individual level. Second, those patterns are not accurately transferred to human skin consistently. Third, it has not been shown that defining characteristics of those patterns can be accurately analyzed to exclude or not exclude individuals as the source of a bitemark.

KEY TAKEAWAY #2.1: The entire human dentition is not represented in a bitemark. Bitemark patterns typically only represent the anterior teeth and thus not the full possible dentition of an individual, limiting the amount of information available for an analysis.

KEY TAKEAWAY #4.1: There is a lack of research into population frequencies, specific identifying characteristics, and measurements that support the notion that human anterior dental patterns as reflected in bitemarks are unique to individuals.

KEY TAKEAWAY #4.2: Accurate transference of an anterior dentition pattern in the form of a bitemark on human skin can be limited by distortions caused by skin elasticity, unevenness of the biting surface, location of the bite, and movement of the biter and/or victim during the biting event.

KEY TAKEAWAY #4.3: Comparisons between bitemark patterns made on skin, for example multiple bitemarks from the same individual on the same victim, have shown that there exists intra-individual variation in bitemark morphology on the human body such that bitemarks from the same biter may not appear consistent.

KEY TAKEAWAY #4.4: Bitemarks in cadaver-based research studies are representative of highly controlled experimental conditions and these results may overestimate the accuracy of analysis methods. Bitemarks in actual cases, where controlled conditions are not present, are prone to higher levels of inaccuracy.

KEY TAKEAWAY #4.5: As reflected in research studies to date, bitemark examiners may not agree on the interpretation of a specific bitemark, including whether the injury is a bitemark, the features present, and the exclusion or non-exclusion of potential biters.

KEY TAKEAWAY #5.1: Repeated calls for additional data by critics and practitioners (since at least 1960) suggest insufficient support for the accurate use of bitemark analysis and a lack of consensus from the community on a way forward.

Calls have been made for empirical studies to assess the limitations of bitemark analysis for decades. Since 1960, those in the bitemark community have been highlighting the lack of empirical research and the need to address reliability concerns in bitemark methods. These calls have largely gone unheeded.

This report describes an examination of publicly available literature and information pertaining to bitemark analysis. If the field seeks to advance, the key takeaways provided in this report are starting points for areas needing improvement, not an exhaustive list of specific shortcomings.

1. Introduction

When a perpetrator bites a victim, the bitemarks[2] can potentially become evidence of a crime. Determining that the injury resulted from a human bite, and identifying the source of the mark (i.e., the biter), requires additional investigation and analysis. The methods used for bitemark analysis have come under considerable scrutiny and debate.

The questions this scientific foundation review poses include:

(1) Can bitemarks be accurately associated with the teeth that left them?

(2) What data exist to support or refute this claim in bitemark analysis?

Bitemark analysis typically involves examining patterned injuries left on a victim or object at a crime scene, identifying those injuries as bitemarks, and comparing those marks with dental impressions from a person of interest (POI). Efforts to perform bitemark analysis involve three key elements (Figure 1.1.): (1) the anterior dentition of the person of interest (the presumed biter), (2) the accurate transfer of the biter's dentition to a surface (such as human skin) to produce a bitemark, and (3) image analysis of the putative bitemark to recover the dental pattern, compare this pattern to the person of interest's dentition, and interpret the results.

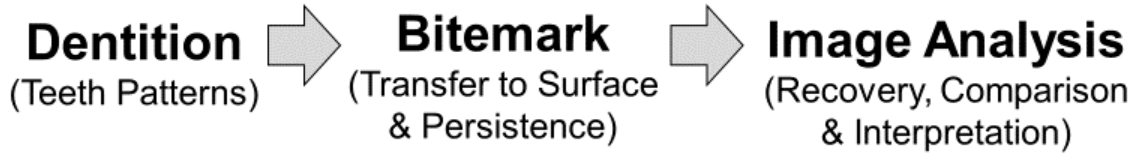

Figure 1.1. Three key elements of bitemark analysis.

Three primary premises are important for successful bitemark analysis: (1) that dental characteristics, especially the arrangement of the anterior teeth, differ substantially among individuals (i.e., uniqueness), (2) skin or other marked surfaces can reliably capture those differences (i.e., transference), and (3) a bitemark examiner can accurately compare dentition information with the bitemark image (i.e., interpretation) (Hale 1978, Pretty & Sweet 2001, Saks et al. 2016). This review found that these three premises are not supported by the data. Therefore, the ability of bitemark analysis to accurately exclude or not exclude individuals as a source of the mark is not supported.

KEY TAKEAWAY #1.1: Forensic bitemark analysis lacks a sufficient scientific foundation because the three key premises of the field are not supported by the data. First, human anterior dental patterns have not been shown to be unique at the individual level. Second, those patterns are not accurately transferred to human skin consistently. Third, it has not been shown that defining characteristics of those patterns can be accurately analyzed to exclude or not exclude individuals as the source of a bitemark.

[2] This report uses the term bitemark or bitemarks as one word rather than two words or as hyphenated words. The singular word usage "is considered a more progressive term, signifying that odontologists have accumulated a sufficient body of knowledge to dignify the form," according to Mark L. Bernstein in chapter 5 of *Bitemark Evidence: A Color Atlas and Text, Second Edition* (2011), edited by Robert Dorion.

This review does not explore the whole discipline of forensics odontology, which includes, for example, comparing antemortem dental records to postmortem X-rays of the full dentition to identify human remains. Instead, the focus is primarily on bitemarks left on human skin as they potentially relate to a crime.

This foundation study on bitemark analysis aims to promote a better appreciation of the capabilities and limitations of the practice within the forensic community as well as among other stakeholders, including investigators and legal professionals. Given the questions already arising from practitioners within this field about the legitimacy of the fundamental assumptions required to establish a verifiable source of a bitemark (Avon et al. 2010) and the frequency at which such claims are disproven with DNA testing (Bowers 2006), this review also focused on the limitations inherent to this practice and under what conditions are they being observed.

1.1. Issues Considered and Approaches Taken

A two-day workshop was held in October 2019 with representatives of relevant communities and stakeholders including odontologists, statisticians, researchers, and lawyers. This event provided diverse perspectives on the current practices of forensic bitemark analysis and enabled small group discussions on topics important to scientific foundations of the practice. The full report from the October 2019 CSAFE Thinkshop is available at https://doi.org/10.6028/NIST.IR.8352sup1.

A bitemark examiner attempts to exclude or not exclude an individual as being the source of a bitemark under the premises that (1) human dentition is unique at the individual level, (2) that uniqueness can be accurately transferred as a bitemark, persist, and be recovered from the material bitten, and (3) identifying characteristics can be accurately captured and interpreted by analysis techniques. In other words, bitemark analysis and comparison propose that there are unique characteristics of human teeth that transfer patterns to bitten surfaces and these characteristics can be successfully recovered and analyzed to exclude or not exclude individuals as the source of bitemark.

To assess these issues, we surveyed existing literature in three areas: bitemark analysis on anterior dental morphology and distinguishing characteristics between individuals, how those characteristics might transfer and persist in human skin, and empirical studies on the accuracy of bitemark comparisons, with the goal of identifying the strengths, weaknesses, and knowledge gaps in the field.

1.2. Limitations

A report such as this one provides a snapshot of the current state of the field. Any literature review, no matter how comprehensive, will be out-of-date as soon as it is published. In addition, since only published articles or publicly available information and data were sought, some existing information retained by practitioners may not have been available for review.

The authors of this foundational review are neither lawyers nor forensic odontologists. This provides an opportunity for a neutral and fresh perspective, but also means that some material

may have been missed in the review due to inaccessibility. By initially providing this report in draft form for public comment, we seek input on sources of information that may have been overlooked.

As with any field, the scientific process (research, results, publication, additional research, etc.) continues to lead to advancements and better understanding. Information contained in this report comes from the authors' technical and scientific perspectives and review of information available to us during the time of our study. Where our findings identify opportunities for additional research and improvements to practices, we encourage researchers and practitioners to act to strengthen methods used to move the field forward.

1.3. Authors and Input Received

The review team consisted of four individuals from the National Institute of Standards and Technology (NIST) whose diverse expertise permitted examination of issues from many perspectives including lessons learned in other fields. Table 1.1. lists members of the review team, their NIST operating unit, and their expertise.

Table 1.1. NIST review team and their areas of expertise.

Name	NIST Operating Unit	Areas of Expertise
John M. Butler	Special Programs Office	Forensic DNA, scientific literature, and research
Karen K. Reczek	Standards Coordination Office	Documentary standards
Christina Reed	Special Programs Office	Communications and science writing
Kelly Sauerwein	Special Programs Office	Biological anthropology

Assistance in finalizing this report was also provided by several additional NIST employees or contractors as noted in the Acknowledgments. Members of the bitemark analysis community and various stakeholders provided important input as part of a steering committee (Table 1.2.) that organized the two-day Bitemark Thinkshop.

Table 1.2. Bitemark Steering Committee (listed in alphabetical order) that met via teleconference multiple times in 2018 and 2019 to plan the Bitemark Thinkshop held in October 2019.

Name	Affiliation	Role
Robert Barsley	Louisiana State University	Odontologist
Mary Bush	University of Buffalo	Odontologist
John Butler	NIST Special Programs Office	Researcher

Name	Affiliation	Role
Alicia Carriquiry	Iowa State University	Statistician
Rich Cavanagh	NIST Special Programs Office	Researcher
Bonner Denton	University of Arizona	Researcher
Barbara Hervey	Texas Court of Appeals	Judge
Donna Kimball	NIST Special Programs Office	Logistics
Gerald LaPorte	Florida International University (previously National Institute of Justice)	Researcher
Bill MacCrehan	NIST Chemical Sciences Division	Researcher
Willie E. May	Morgan State University (former NIST Director)	Researcher
John Morgan	RTI International	Researcher
Christopher Plourd	Imperial County Superior Court	Judge
Rich Press	NIST Public Affairs Office	Communications
Karen K. Reczek	NIST Standards Coordination Office	Standards
Hal Stern	University of California – Irvine	Statistician
Richard Vorder Bruegge	FBI Laboratory & OSAC Forensic Science Standards Board (FSSB)	Researcher & Practitioner
Isiah Warner	Louisiana State University	Researcher

1.4. Report Structure

This report contains five chapters. Following this introductory chapter, Chapter 2 provides background information on bitemarks and describes the principles and practices involved in bitemark analysis and comparison. Chapter 3 lists the data sources used and how they were located. Chapter 4 discusses important aspects that influence the accuracy of bitemark data. Chapter 5 provides conclusions and thoughts on future directions for the field.

Supplemental information to this report is also available at https://www.nist.gov/forensic-science/scientific-foundation-review-bitemark-analysis. This material includes the full report of the 2019 CSAFE Bitemark Thinkshop, available standards and guidelines for forensic odontology, a brief history of public criticisms of bitemark analysis, and the full reference list of publications examined as part of this study.

The initial release of this report is as a draft document, and we welcome comments and feedback from readers. All relevant submitted comments will be made publicly available and will be considered when finalizing this report. When submitting feedback, do not include personal information, such as account numbers or Social Security numbers, or names of other individuals. Do not submit confidential business information, or otherwise proprietary, sensitive, or protected information. We will not post or consider comments that contain profanity, vulgarity, threats, or other inappropriate language or like content. During the public comment period, please send comments to scientificfoundationreviews@nist.gov.

2. Background on Bitemark Analysis

2.1. Elements of Bitemark Analysis

2.1.1. Dentition Characteristics

The American Board of Forensic Odontology (ABFO) defines a bitemark as a "physical alteration or representative pattern recorded in a medium caused by the contact of teeth of a human or animal." For human bitemarks, this pattern would demonstrate features, traits, or characteristics that distinguish the patterned injury as a bitemark (ABFO 2018). Included in these class characteristics are measures of size and shape, arrangement, wear and tear, damage, age, quality, number of individual teeth, prostheses, and replacements (Levine 1977, Verma et al. 2013). During the comparison of a dental impression from a possible suspect with the bitemark pattern under investigation, several factors are examined including indentations, chips, abrasions, striations, distances between cusps, tooth width and thickness, alignment, and mouth arch (van der Velden et al. 2010, Verma et al. 2013).

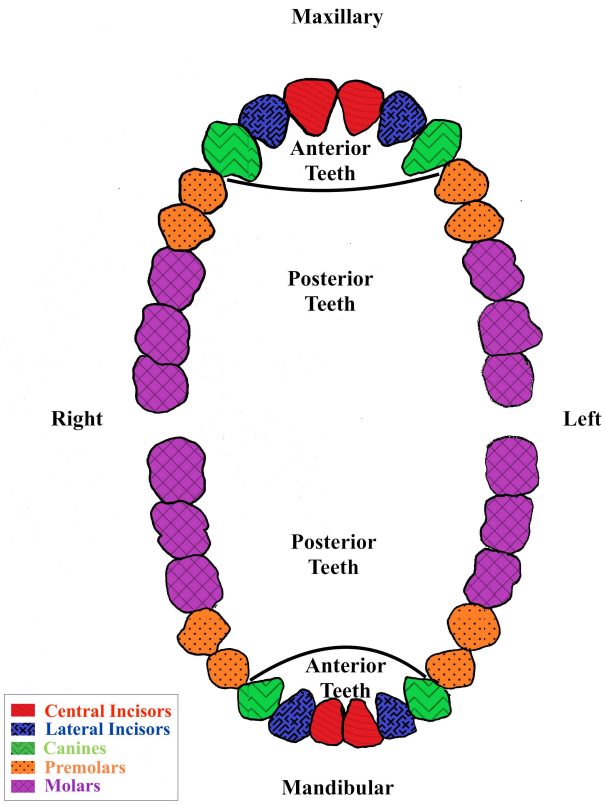

Figure 2.1. Illustration of a typical human dentition viewed in standard anatomical position.

Each tooth type in the human dental arcade has class characteristics that differentiate one type from the others. The anterior teeth, including central and lateral incisors and canines, are most

often involved in a bitemark (Figure 2.1.). Bitemark characteristics aid in determining which marks were made from maxillary or mandibular teeth. Missing teeth, tooth injuries, breakages, or something obstructing a tooth from the biting surface can account for gaps seen in bitemarks (Sweet & Pretty 2001).

Individual characteristics are features or traits that distinguish one person, or their teeth, from any other. Examples of individual characteristics are those found in the arch (shape, size, tooth displacement rotation, or drift) and individual teeth (wear pattern, chips, notches, fractures, or other anomalies).

> **KEY TAKEAWAY #2.1: The entire human dentition is not represented in a bitemark. Bitemark patterns typically only represent the anterior teeth and thus not the full possible dentition of an individual, limiting the amount of information available for an analysis.**

2.1.2. Challenges with Bitemarks on Skin

According to the ABFO (2018), bitemark data has been utilized to document aspects of violence, provide a potential link between victim and perpetrator, and help support or refute the history of events reported or discovered in a legal context. The distortions, elasticity, and evenness of the surface of the object bitten factor into whether a bitemark is produced and can be accurately analyzed considering the distortions, elasticity, and evenness of the specific biting surface. In food or compressible objects other than skin, the pattern is more often visible as a result of tooth indentations or impressions and occurs with sometimes little force exerted by the biter (e.g., bitemarks left in Styrofoam, wax, or cheese).

On skin, the pattern is seen as a vital response to the injury through swelling, scraping (abrasion), bruising (contusion), or tearing (laceration). Depending on the force of the bite and the skin itself, the tissue may not show a response and therefore some bites may not leave a mark (Bernstein 2011).

In addition, human skin can change the appearance of a bitemark over time depending on the rate and amount of swelling at the site, healing, and skin elasticity; location of the bitemark can exacerbate these factors and lead to greater distortions (Pretty & Sweet 2001, Vilborn & Bernitz 2021). According to Mark L. Bernstein of the University of Louisville School of Dentistry: "Bleeding or scraping of skin under assault are not obliged to conform precisely to the anatomy of the object that produced it" (Bernstein 2011). In this way, human skin as a dependable material for bitemarks is a key area of dispute in the field.

2.1.3. Available Guidance Documents

The American Board of Forensic Odontologists (ABFO) updated their updated guidelines in 2018 for collecting and evaluating bitemark data from both victims and alleged biters. These steps are summarized in Table 2.1. An evaluation of bitemark data includes:

(1) Examination of questioned pattern to determine whether it is a bitemark
(2) Interpretation and analysis of bitemark features
(3) Comparison of bitemark data to that of POIs and foil (i.e., non-POIs) dentitions
(4) Formation of opinions, if possible, on whether subject and foil dentitions can be excluded or not excluded as the cause of the bitemark pattern

Table 2.1. Steps in the evaluation of bitemark data (based on ABFO 2018).

Evaluation	Procedure
Determination of Pattern as Bitemark	Take photographs of mark, including its location and size Identify mandibular/maxillary arches and midline Determine whether visible marks caused by individual teeth are identifiable Determine whether size/shape of arch is comparable to normal human variation
Interpretation and Analysis of Bitemark Features	Locate pattern and identify features, (e.g., size, shape, anomalies) Take photographs establishing location and features Swab for biological evidence Take impressions of bitemark and victim's dentition to be turned into casts for further assessment
Bitemark Comparison Methods	Generate overlays, including hollow volume, solid volume, semitransparent representations; computer-generated 2D/3D scans of subject dentition, 2D photographs of teeth or casts, or 2D/3D scans of casts Collect test bites in medium that may include dental wax, animal or human skin, or other media. Test bites can be used to create overlays Additional methods - transillumination, computer enhancement and/or digitization of the mark or teeth, stereomicroscopy, scanning electron microscopy (SEM), video superimposition, and histology
Formation of Conclusions (Levels of Certainty)	Exclude as having made the bitemark Not exclude as having made the bitemark Inconclusive Terms indicating "match" or unconditional linkage to a single dentition are not sanctioned by ABFO

Of note is the terminology ABFO established limiting the level of certainty an analyst can conclude from their evaluation of a bitemark and the suspected dentition involved in making that mark. No dentition is considered as the cause of or a match per se to a specific bitemark. The language used in this AFBO 2018 document, excluded, not excluded, or inconclusive, indicates a general sense of uncertainty with any of these conclusions.

2.2. Key Areas of Dispute

Reliability over the following aspects of bitemark analysis remain key areas of dispute: human skin as an accurate registration material for bitemarks, the uniqueness of human dentition, and analysis techniques and conclusions.

The ABFO guidelines for bitemark analysis, first published in 1986, have been an attempt to standardize the collection and analysis of bitemark data. A previous review of bitemark analysis (NRC 2009) noted disagreement amongst odontologists about standards for comparison and that usage of these guidelines is voluntary.

A 2003 study documented adherence to the 1997 version of the ABFO guidelines (McNamee & Sweet 2003). While practitioners were generally compliant with evidence collection procedures advocated in the ABFO guidelines, the areas of photographic documentation as well as impression and excision of the bitemark site lacked consistent adherence and were susceptible to personal preferences of the examiner. As of early 2022, there has been no recent information about adherence to the current 2018 ABFO guidelines, so it is unknown whether these past issues have improved.

3. Data and Information Sources

To assess accuracy and other relevant issues related to bitemark analysis and comparison, empirical data and information were sought from publicly available sources including peer-reviewed scientific publications, documentary standards, and guidelines.

The NIST Special Programs Office requested the Center for Statistics and Applications in Forensic Evidence (CSAFE), a NIST Forensic Science Center of Excellence, to organize a Bitemark Thinkshop in October 2019 to gather input from the community and its stakeholders. In addition, RTI International (Raleigh, NC), which currently serves as the National Institute of Justice (NIJ) Forensic Technology Center of Excellence[3], provided a list of bitemark analysis articles they considered under a separate systematic review of bitemark data in criminal matters.

3.1. Literature Review

Literature – including peer-reviewed publications, reports, and books–was compiled from a variety of sources described below. These resources primarily addressed the key assumptions of bitemark analysis: uniqueness, transference, and interpretation.

3.1.1. RTI Literature Review

The NIJ Forensic Technology Center of Excellence within RTI International began a systematic review of the bitemark literature in 2018. In consultation with leading bitemark practitioners and researchers, RTI compiled a list of over 100 peer-reviewed journal articles determined to be relevant to their assessment of the bitemark literature. In November 2019, RTI provided an initial version of their list to NIST – consisting of the title, reference, and abstract for each article evaluated. An updated list was provided in April 2021.

3.1.2. NIST Assessment of the Literature

The list provided to NIST from RTI International was compared to the ABFO 2011 annotated bibliography that was submitted in response to a request by the Subcommittee on Forensic Science (Butler 2015), as well as a 2011 annotated bibliography compiled by Mary Bush, Peter Bush, and Iain Pretty (TXFSC 2016). These annotated bibliographies consisted of peer-reviewed original research papers, review articles, and books. NIST conducted an additional literature search covering the years of 2010 through 2021. After duplicate references were eliminated, a total of 403 unique bitemark references remained. The full reference list is available as supplemental document at https://doi.org/10.6028/NIST.IR.8352sup4.

Articles examined came from the following journals: *Journal of Forensic Sciences, Forensic Science International, Journal of Forensic Odontostomology, Journal of Forensic Identification, Journal of the Forensic Science Society, Science & Justice, Journal of Visual Communication in Medicine, International Journal of Legal Medicine, Research Journal of Medical Sciences, Journal of the American Dental Association,* and the *American Journal of Forensic Medicine and Pathology*.

[3] See https://forensiccoe.org/

Sources were evaluated based on their applicability to one of the underlying assumptions of bitemark analysis – uniqueness, transference, or interpretation – and their use of empirical methods to assess these assumptions. Sources with empirical data were given priority over case reports, commentary, legal reviews, opinion pieces, and other similar publications.

3.2. Workshop Discussion (October 2019 CSAFE Bitemark Thinkshop)

At the start of this NIST scientific foundation study on bitemark analysis, a workshop was envisioned as the most effective means of bringing various stakeholders together to discuss current perspectives on issues. Rich Cavanagh and Karen Reczek of NIST formed an 18-member steering committee (see Table 1.2.) composed of NIST staff and external stakeholders who met multiple times via teleconferencing from Spring 2018 until Summer 2019 to plan the event.

Early in the process, the steering committee decided on organizing a *thinkshop* rather than a workshop. A workshop involves a brief intensive educational program for a relatively small group of people that focuses especially on techniques and skills in a particular field, while a thinkshop is more exploratory and focuses on open challenges and knowledge gaps. The steering committee selected the invited participants and introductory speakers, defined the meeting format, and decided on topics for discussion.

The Center for Statistics and Applications in Forensic Evidence (CSAFE)[4] was engaged through a NIST grant to execute the thinkshop. NIST contracted with SNA International to serve as breakout session facilitators and meeting notetakers. Invited participants represented a cross-section of individuals working in forensic odontology and other disciplines and included: forensic image experts, measurement scientists and researchers, forensic scientists, legal experts such as prosecutors, defense attorneys and victim advocacy groups, and statisticians. Forensic odontologists with differing views on the use of bitemark data were actively sought.

The meeting was held over two days in October 2019. The full thinkshop report, which CSAFE and SNA International provided to NIST, is available at https://doi.org/10.6028/NIST.IR.8352sup1.

Day one began with six speakers providing introductory remarks to the entire group. Participants were then divided into three groups of 12 to 15 individuals to discuss one of three specific questions (Box 3.1). The composition of each discussion group was shuffled over the two-day event to maximize exposure to different perspectives. During the meeting everyone had an opportunity to discuss every question. At the end of each breakout session, the entire group reconvened to hear a summary of what had been discussed in each discussion group. The thinkshop concluded with all participants gathering for a moderated discussion on conclusions, takeaways, and next steps.

[4] See https://forensicstats.org/

Box 3.1 Bitemark Thinkshop Science Questions

Science Topic #1 (Dentition): Are there measurable characteristics or features in human dentition that vary among individuals and are persistent within an individual?
Claim: Characteristics of human dentition are unique or can be divided into reliable fractions of the population, provided consideration of any changes with morphometric parameters over time and events.
Focus Area A: What measurement method(s) provide the best information for capturing reliable information about the dentition? Focus Area B: How do we appropriately collect information to create population databases that can be used for scientific and statistical analysis of human dentition? Focus Area C: What are the most probative features/parameters to use, and what are the limits associated with each?

Science Topic #2 (Bitemarks): Do bitemarks transfer measurable characteristics of the dentition to the substrate?
Claim: Bitemarks in human skin and other substrates reliably reflect the features of dentition.
Focus Area A: What imaging and measurement method(s) provide the best information for capturing reliable and reproducible information about the bitemark? Focus Area B: What contributes to the variability in bitemarks from dentition, and how can the variability be determined? Focus Area C: What data collection techniques are sufficient to collect evidence of pattern injuries on human skin?

Science Topic #3 (Analysis and Interpretation): What interpretation strategies (techniques and practices) produce the most accurate and reliable results?
Claim: Selected data interpretation strategies produce more reliable/defensible results.
Focus Area A: What defines sufficiency to establish reliability in the association of bitemarks to dentition? Focus Area B: What other data are relevant to bitemark examination and analysis? Focus Area C: What are the key approaches to take in bitemark analysis that will ensure the comparison is objective and, if the dentition is not excluded, the significance of an association is accurately reported?

3.3. Documentary Standards and Guidelines

In the area of bitemark analysis, the American Board of Forensic Odontology (ABFO) has developed and published the ABFO Standards and Guidelines for Evaluating Bitemarks (ABFO 2018). The process used to develop this ABFO document is not known.

In odontology there are several standards developing organizations (SDOs) that are developing, and publishing standards related to forensic odontology, but not necessarily to bitemark analysis specifically. Newer standards being developed are using the terms “suspected pattern injury or patterns produced by human dentition” in lieu of the term “bitemarks.” Additional information related to available standards in odontology is available at https://doi.org/10.6028/NIST.IR.8352sup2

4. Exploring Factors Influencing Reliability of Bitemark Analysis

As discussed in Chapter 2, three primary postulates are important for successful bitemark analysis: (1) that dental characteristics, especially the arrangement of the anterior teeth, differ substantially among individuals (i.e., uniqueness), (2) skin or other marked surfaces can accurately capture those distinctions (i.e., transference), and (3) a bitemark examiner can accurately compare dentition information with the bitemark image (i.e., interpretation) (Hale 1978, Pretty & Sweet 2001, Saks et al. 2016) to exclude or not exclude POIs.

In each section below, a brief review of the literature of findings on the topics of uniqueness, transference, and interpretation is provided as well as a summary of observations on those specific topics from the 2019 Thinkshop (CSAFE 2019). The Key Takeaways highlight important findings and observations.

4.1. Uniqueness of Human Dentition

The premise that every individual's dentition is unique is fundamental to the process of comparing a person of interest's (POIs) dentition with a bitemark pattern found on a victim. Yet examination of uniqueness and the null hypothesis that another person with similar dentition could provide an equally plausible bitemark, has produced conflicting results. In addition, only the anterior teeth of an individual's dentition are typically involved in creating a bitemark (see Section 2.1.1), so the full dentition is not usually included in the comparison.

This concept of uniqueness is a strong point used in the analysis of bitemark data to convince courts that the dentition of one individual is different from other individuals (e.g., Verma et al. 2013, Martin-de-las-Heras et al. 2005) with some comparing dentition to fingerprints or DNA (Rawson et al. 1984, Verma et al. 2013). However, uniqueness has remained a controversial point among practitioners. Critics note disagreements on the specific characteristics needed to establish dental uniqueness and the lack of population frequencies that indicate a degree of variation in dental features (Saks et al. 2016, CSAFE 2019).

In 1960, Ron W. Fearnhead of the Departments of Anatomy and Dental Histology at the London Hospital Medical College conducted a study to examine the match accuracy between dental models and their corresponding bitemarks made in foods such as cheese, apples, and chocolate as well as to determine whether two models could ever match the same bitemark. He found that not only could he correctly match the models of teeth to their corresponding bitemarks, but he also identified a separate dental model, not associated with the initial study or any of the bitemarks, that matched the marks "just as perfectly as the models of the jaws that made them" (Fearnhead 1960). This study highlighted the need for more training and research into the forensic odontology to prevent the community from "the danger of accepting, too readily, evidence which at first sight appears to be based on an exact science" (Fearnhead 1960).

One of the most frequently cited studies that purported to support the uniqueness of human dentition utilized computer comparisons of the dental patterns of monozygotic twins (Sognnaes et al. 1982). This study stated that there were differences in tooth measurements between twins and bilateral asymmetry within individuals. That is, within twins, the anterior teeth did not reach the same horizontal plane at the incisal edges. However, Sognnaes and colleagues only studied

five pairs of twins and while they used a computer-based overlay to compare each twin to the other, the authors did not provide any quantitative measures of similarity or error (Sognnaes et al. 1982).

Another study (Rawson et al. 1984) investigated statistical probability of two individuals having the same number of teeth in matching positions. Using 397 radiographs of wax bite cards provided by dentists in the United States, the authors estimated that the number of possible combinations of tooth positions in the lower jaw alone is 6.08×10^{12} (i.e., 1 in 6 trillion) and it would only take a match of 5 teeth in order have "confidence that there would be no other set of teeth capable of producing the same match" (Rawson et al. 1984). However, they do not state what is meant by 'confidence' or how their U.S. sample can be generalized to the world's population. They also neither examined the possibility that tooth positions may be correlated with one another nor did they compare the individual bitemarks with each other to confirm their conclusions (Rawson et al. 1984). While Rawson's (1984) findings have been supported by other research (Bernitz et al. 2006, Kieser et al. 2007) that claim tooth rotation and arch size and shape are potentially individualizing characteristics, these evaluations systematically lack population frequencies and details on measurement bias that may impact their conclusions.

A 2011 study (Bush et al. 2011a) reproduced the statistical analysis Rawson made in 1984 and found a nonuniform distribution of tooth position within human dentition and concluded that inferences about the uniqueness of human dentition with purposes for bitemark analysis are not supported. The 2011 study also found that similarities among 3D scans of 344 dental casts occurred more often than in Rawson's original findings, casting strong doubt on the 1-in-6 trillion claim (Bush et al. 2011a). Therefore, any claims that the Rawson study establishes population frequencies for bitemark patterns could be considered premature.

In 2015, a meta-study of over 1,200 articles identified in electronic library database searches found only four studies claiming results indicating uniqueness and nine other studies that found positive matches between different dentitions (Franco et al. 2015). This meta-study concluded that "the uniqueness of human dentition was not scientifically proven" based on the lack of sample size/power analyses, appropriate statistical methods, 3D data, and intra- and inter-examiner analyses.

Participants at the 2019 CSAFE Thinkshop weighed in on the question of the uniqueness of human dentition and they concluded that such a question was no longer relevant to the field because it is "highly unlikely" that characteristics exist that could be used to define dental individuality (CSAFE 2019, section 3.1.2.). Furthermore, the 2018 ABFO Standards and Guidelines do not condone conclusions that "unconditionally link" a bitemark to a specific dentition (ABFO 2018, section 1-f). Instead, suspect dentitions should be excluded or not excluded as having made a bitemark. Thinkshop participants did note that the question of uniqueness may not even be relevant with the use of exclude or not exclude conclusions. As odontologists are looking to determine the prevalence or rarity of an individual's dental pattern, reliable and scientifically based methods are required to reduce the chance of an incidental association with someone who should be excluded. Understanding the frequency of class characteristics in a population is necessary to support a conclusion of excluded or not excluded. The thinkshop participants also discussed the uniqueness question indirectly when they identified

the need for standard protocols, definitions for dental measurements, databases, and consensus for what features should be measured to characterize an individual's dentition (CSAFE 2019, section 3.1.1. to section 3.1.2.).

KEY TAKEAWAY #4.1: There is a lack of research into population frequencies, specific identifying characteristics, and measurements that support the notion that human anterior dental patterns as reflected in bitemarks are unique to individuals.

4.2. Transfer and Persistence of Bitemarks

Bitemark analysis is also based on the assumption that the individual characteristics of the biter's anterior dentition will be accurately transferred to the substrate. Several studies have been conducted utilizing media other than skin, such as wax (Whittaker 1975, Rawson et al. 1984, Blackwell et al. 2007), Styrofoam (Pretty 2011), cheese (Layton 1966, Ligthelm et al. 1987), and apples (Rudland 1982, Ligthelm et al. 1987). However, to be able to generalize to cases where people bite other people, skin as a substrate must be studied experimentally.

Skin deformation substantially distorts the bitemark in such a way that analysts may be unable to accurately exclude or not exclude a POI. It has been well-documented that bitemarks recorded in skin have displayed varying degrees of distortion (Sheasby & MacDonald 2001, Bush et al. 2009, Pretty & Sweet 2010, Sheets et al. 2012, Lewis & Marroquin 2015, Dama et al. 2020). There are many factors that contribute to the degree of distortion present in a bitemark, including bite force, surface area and alignment of the dentition, tooth sharpness, elasticity of victim's skin, movement during the biting event, and the body's injury response (e.g., swelling, bruising, and healing) (Bush et al. 2009, Bush et al. 2010b, Miller et al. 2009, Lewis & Marroquin 2015). For example, in exploring the role of skin elasticity in bitemark distortion, Lewis & Marroquin (2015) utilized partial tooth dental stamps that were placed on the curve of the shoulders of 40 volunteers who held their arms in 1 of 4 positions – 1) arms by sides/hands on lap, 2) arms straight out, 3) arms across the chest/hands on opposite shoulders, or 4) hands held behind the back. Photographs were taken of each mark, and measurements of individual tooth widths and mesial to distal and intercanine distances were recorded. Overall, Lewis & Marroquin (2015) found that distortions increased depending on body position. Tooth width and arch width distortions were as high as 53.8% and 41.9%, respectively. They also found that bitemark patterns were unpredictable because distortions were not uniform across the dental arches. While this study is limited to a single location on the body, it suggests that skin elasticity and body position are critical variables to be considered when examining a bitemark.

Skin's anatomical makeup includes biomechanical properties that make skin pliable and elastic while having considerable tensile strength and toughness (Jablonski 2013). These viscoelastic properties influence how the tissue responds to a bite.

Studies on bite forces, skin elasticity, and mark distortion document changes in flattening or constriction of the arch, rotation or displacement of teeth, significant deviation in overall alignment, the appearance of a missing tooth or diastema although none is present in the source dentition, mesial-distal width, angles of rotation, and intercanine widths depending on the

tightness of the skin at the time the bite occurs (Bush et al. 2010b, Lewis & Marroquin 2015, Dama et al. 2020). This is because skin's properties are based on lines of tension that describe the magnitude of the stress placed on the skin. In the direction parallel to skin tension, tissue is inherently tighter, while perpendicular to skin tension, the tissue is looser. The degree and direction of tension differs according to the location on the body, body movement, and position (DeVore 1971, Sheasby & MacDonald 2001, Bush et al. 2009, Dama et al. 2020).

One study indicated that firmer tissues such as skin over muscle respond differently when bitten than skin that was looser or covered fatty tissues (Bush et al. 2009). Another study showed that all bitemarks used in their research showed some degree of distortion, especially regarding arch width, which had "extensive and unpredictable" distortions (Sheets et al. 2012).

KEY TAKEAWAY #4.2: Accurate transference of an anterior dentition pattern in the form of a bitemark on human skin can be limited by distortions caused by skin elasticity, unevenness of the biting surface, location of the bite, and movement of the biter and/or victim during the biting event.

In addition, Mary Bush and colleagues (Bush et al. 2009) found that multiple bites from a single dentition showed significant distortions such that no two bitemarks appeared the same. If bitemarks with the same dentition display such significant distortions that they are not reproducible from simulated bite to bite, this raises concerns about the accuracy of bitemark analysis in general and more specifically, the probability that an innocent person can be accurately excluded as the source of a bitemark.

KEY TAKEAWAY #4.3: Comparisons between bitemark patterns made on skin, for example multiple bitemarks from the same individual on the same victim, have shown that there exists intra-individual variation in bitemark morphology on the human body such that bitemarks from the same biter may not appear consistent.

During the 2019 Bitemark Thinkshop, discussion regarding transfer and persistence of bitemarks focused on marks made on skin; no other material was discussed. Participants concluded that a bitemark impression in skin would not record sufficient detail to make an identification at an individual level and that current imaging methods do not capture all characteristics necessary for bitemark analysis as these methods cannot determine the force of the bite, bruising depth, or movement during the bite (CSAFE 2019, sections 4.1.1 - 4.2). Furthermore, they concluded that fundamental research is needed on how bitemarks are transferred to skin specifically with attention to identification of the variables that affect bitemark pattern appearance and how skin may distort the bitemark injury.

Research testing the assumption of accurate transference and persistence of bitemarks has mostly relied on the use of human cadavers or nonhuman analogues for the biting substrate. For example, one study examined the accuracy of bitemark comparisons by creating exemplar bites in pig skin (Whittaker 1975). Aside from ethical concerns related to the use of animals in scientific research, animal skin only partially mimics the features of human skin (Steadman et al.

2018, Dellambra et al. 2019), making generalizations to humans difficult. Pigs are commonly used in research because their skin is similar to human skin in terms of cell composition, physiology, and thickness; the biggest difference is a thicker fat layer in pigs (Dellambra et al. 2019). However, as pigs are not humans, researchers need to be careful about generalizing results found using non-human analogues.

In addition to non-human proxies, numerous studies have utilized cadaver models for bitemark analysis (Bush et al. 2009, Miller et al. 2009, Bush et al. 2010a, Bush et al. 2010b, Sheets & Bush 2011, Bush et al. 2011b, Holtkoetter et al. 2013). Because the skin of cadavers loses elasticity over the postmortem period and does not undergo changes caused by inflammatory reactions following the bite, it is important to appreciate that the substrate used in the cadaver research is different than that of a living victim. Marks may not be distorted by movement, swelling, bruising, or healing. Cadaver-based research employs an unchanging material under highly controlled conditions and the results may imply a greater accuracy than can be found in criminally inflicted bites on living individuals. However, those conditions aside, research with cadaver models has found high levels of variability and incorrect identifications even under these somewhat controlled conditions. One study found upwards of 16% of foil dentitions could not be excluded as the biter (Miller et al. 2009), while another found 38% of bitemarks in their sample showed distortions significant enough where an innocent person might not be excluded as the biter. Bitemarks in actual cases, where those controlled conditions often do not exist, can be expected to be prone to higher levels of inaccuracy.

KEY TAKEAWAY #4.4: Bitemarks in cadaver-based research studies are representative of highly controlled experimental conditions and these results may overestimate the accuracy of analysis methods. Bitemarks in actual cases, where controlled conditions are not present, are prone to higher levels of inaccuracy.

The 2019 CSAFE Thinkshop participants repeatedly concluded that fundamental research studies need to be conducted to identify a standard set of features and measurements to characterize human bitemarks as well as to determine the resolution needed for imaging the mark. Currently there is no consensus on what features can be used to accurately determine whether a pattern injury is a human bitemark (CSAFE 2019, section 4.1.1). Such studies would need to include a wide range of injuries made in skin on different locations on the body with different degrees of force, some human-derived, some from animals, and some from other causes. The attendees at the Thinkshop conceded that it may not be possible to determine all the causal factors involved in a bitemark under controlled conditions because even in a controlled, well-planned study, the risk to participants might be too great to obtain institutional review board (IRB) approval (CSAFE 2019, section 4.1.2).

The findings from animal and cadaver-based research studies demonstrate variability and indicate that the accurate and consistent transfer of bitemark patterns onto human skin, which is central to bitemark analysis, is questionable.

4.3. Interpretation of Bitemark Data

Once a pattern injury is suspected to be a bitemark, photographs (with appropriate scale) are taken, and the bitemark is inspected to determine whether there are any identifiable marks corresponding to maxillary or mandibular arches and/or visible tooth impressions (see Table 2.1.). If those features are present, those marks are then identified as being consistent or not consistent with human dental morphology (ABFO 2018). After the initial analysis of the bitemark is completed, if the data is sufficient to conclude a pattern injury is a human bitemark, comparisons of the bitemark to POIs' dentitions are conducted. These comparisons can be made using overlays, either computer or manually generated, test bites, digitization and computer-aided imaged enhancement, stereomicroscopy, and/or scanning electron microscopy (ABFO 2018). These comparisons may then support a bitemark analyst's opinion that a POI's dentition is excluded as having made the bitemark, not excluded as having made the bitemark, or inconclusive. These conclusions and all associated data should be included in the analyst's final report.

4.3.1. Methods of Analysis

After a pattern injury has been identified as a potential bitemark and data on that mark's characteristics has been gathered, analysts use several techniques to identify the injury as a human bitemark and subsequently exclude or not exclude a dentition as the source of the mark.

4.3.1.1. Overlay Comparisons

Overlays are one method for comparing a POI's dentition to a bitemark. In a traditional overlay, the incisal or biting edge of the cast of the POI's anterior teeth are hand traced onto a transparent sheet that is then placed over the bitemark or a cast of the bitemark to determine whether they correspond (McNamee et al. 2005). Some early methods for producing bitemark overlays included radiographic techniques utilizing metal filings painted into bitemark indentations (Sognnaes 1977), various photographic techniques (Furness 1968, Havel 1985), tracing the incisal edges onto an acetate sheet that was then placed over a 1:1 photo of the teeth (Bernstein 1983), and applications involving CAT scans (Rawson 1990) and commercial photocopiers along with hand-traced perimeters of the teeth (i.e., xerographic methods) (Dailey 1991). Once the overlay is made, the pattern, size, and shape of the POI's teeth are compared to the bitemark. However, some degree of subjectivity is involved in the traditional, hand-traced methods (Sweet et al. 1998). The accuracy of the overlay can be limited by the quality of the photo, scan, or photocopy used to create the hand traced outline of the teeth as the individual tooth perimeters may be difficult to determine. This subjectivity may lead to errors in the overlays which can make it difficult to reach an accurate conclusion.

Recent advances in digital scanning technology have produced bitemark overlays for comparisons with POI dentitions, providing a higher-quality image than provided by the hand-drawn methods. Tai and colleagues (2016) compared the accuracy of bitemark analysis between three methods: xerographic overlay (e.g., photocopy) with hand tracing, computer-assisted overlays, and animated superimposition. Based on a 0-3 scoring system where 0 is "totally unmatched" and 3 is a "definite match," the animated superimposition method was scored the highest, meaning that it produced a higher number of probable and definite matches. The

superimposition method allowed for the comparison of not just the biting edges, but lingual (the tooth surface closest to the tongue in mandibular teeth) and palatal (the surface closest to the tongue on maxillary teeth) marking as well (Tai et al. 2016). The xerographic method, however, was scored the lowest and considered the least accurate and most subjective of the three methods tested; it required a certain level of examiner expertise to hand-trace the tooth edges and could not be reproducibly drawn each time a new overlay was generated from the same cast (Tai et al. 2016). The authors did acknowledge that their conditions were ideal because bitemarks were examined immediately after they were made; no time passed during which the marks could have faded, and no bruising or other injury occurred that obscured the marks.

A 2017 study supported the findings from Tai et al. (2016) and reported that computer-aided overlays produced higher-quality images and led to greater accuracy when compared with a cast dentition than both hand-traced overlays and radiopaque wax impression techniques (i.e., a radiopaque substance such as zinc oxide eugenol was applied to the individual tooth impressions) (Pajinagara et al. 2017). In that study, a closed set design was implemented with only three observers judging overlays of 30 cast dentitions. Those observers had different levels of experience, with only one being a forensic odontologist, and given the small number of observers, no generalizations about experience level or accuracy can be made.

Overlay methods used in bitemark analysis to compensate for distortion effects have been shown to be insufficient and arbitrary as distortions can be nonuniform even within the same bite (Bush et al. 2010a). Furthermore, the range and magnitude of these distortions differed both between bites and within each bite making current techniques for compensating for tissue distortion, such as enlarging or reducing a bitemark photograph, inadequate and unreliable. The risk of attempting to compensate for nonuniform distortion effects can lead to an innocent person not being excluded as a POI or the distortion effects being used to explain discrepancies in the mark to include a POI (Bush et al. 2010a). In both cases, this bias could lead to unsupported inclusions of innocent individuals.

4.3.1.2. 3D Scans

Because overlays utilize a 2D image of a 3D structure, potentially valuable information can be lost such as the shape of the dentition, the curvature of the bitten surface, and the depth of tooth penetration into the bitten object (Giri et al. 2019). Furthermore, since bitemarks undergo distortion during both the biting event and the healing process that follows, it has been argued that a scan is a representation of a distorted bitemark (Vilborn & Bernitz 2021). Three-dimensional digital scanning enables accurate and fast recording of bitemarks made in soft substances – such as cheese, chocolate, pears, apples, and human skin – without further distortion of the mark during impression taking (Stols & Bernitz 2010, Naether et al. 2012, Vilborn & Bernitz 2021). A 3D scanner generates point clouds from geometric data gathered from the surface of an object and the object's shape is then reconstructed from the spatial position of the digital data. Two types of 3D scanners – contact and laser – are utilized in bitemark analysis. Contact scanners, also known as point-to-point or linear scanners, scan the surface of an object via a probe and internal sensors determine the spatial positioning of the probe so 3D reconstruction can be achieved. Laser scanners are non-contact devices that emit a

laser beam onto an object's surface and the laser is reflected back to the scanner to reconstruct the object.

A study comparing the accuracy of contact and laser scanners as measured by uncertainty values reported no significant differences between the two types of scanners; uncertainty values ranged from 0.07 mm to 0.39 mm for single linear measurements and upwards of 0.43 mm to 1.15 mm for intercanine distances (Molina & Martin-de-las-Heras 2015). While these two scanning technologies performed similarly, each has its own limitations: Contact scanners are unable to capture surfaces with marked concavity and have a greater potential to inadvertently damage evidence (Molina & Martin-de-las-Heras 2015, Vilborn & Bernitz 2021). Non-contact methods, avoid the problem of possibly damaging the evidence as there is no contact between the scanner and the biting surface. However, they have difficulty detecting sharp edges, especially the incisal edge of the anterior incisors, leading to incorrect depictions of tooth morphology (Molina & Martin-de-las-Heras 2015). When using the 3D laser scanners for dental casts and biting edges in practical forensic cases, these potential sources of error should be considered (Molina & Martin-de-las-Heras 2015, Vilborn & Bernitz 2021).

4.3.2. Agreement Among Analysts

Multiple studies have demonstrated a widespread lack of agreement on conclusions reached with bitemark data, including those relating to whether the mark was indeed a bitemark, features present, and inconsistency in techniques used to analyze bitemarks from one case to the next (Page et al. 2013, Freeman & Pretty 2015, Reesu & Brown 2016). Freeman and Pretty (2015) measured the degree of consensus among bitemark analysts using a preliminary decision tree designed by the ABFO to aid odontologists in their assessment, analysis, and conclusions for bitemarks. Each analyst answered the following three questions for 100 case photos: 1) Is there sufficient data to render an opinion on whether the patterned injury is a human bitemark? 2) Is it a human bitemark, not a human bitemark, or suggestive of a human bitemark? and 3) Does the bitemark have distinct, identifiable arches and individual tooth marks? Overall, only 8% of cases achieved 90% agreement across the three questions. While this study only examined agreement and not accuracy, the lack of agreement among the 39 bitemark analysts casts doubt on the utility of bitemark analysis as a viable method of excluding or not excluding individuals.

A 2016 study of members of the British Association for Forensic Odontology (BAFO) reported similar results as Freeman and Pretty (2015) in that disagreement was found not only between odontologists on whether a patterned injury was a bitemark, whether it was human or animal, or adult or child, but it also found inconsistency within individual odontologists after reassessing the marks eight weeks later (Reesu & Brown 2016). This lack of agreement on the basics of bitemark analysis highlights a fundamental flaw of bitemark analysis methods and casts heavy doubt on the accuracy of the conclusions of such analysis. Similar conclusions have been reached for decades (Whittaker 1975, Whittaker et al. 1998, Arheart & Pretty 2001).

975 The 2019 CSAFE Bitemark Thinkshop tackled this question and determined that there was not
976 enough data to establish the degree to which practitioners can reliably associate bitemarks to
977 individual dentition patterns. They also stressed that practitioners should avoid the term "match"
978 in their interpretations due to the qualitative and subjective nature of bitemark analysis (CSAFE
979 2019). This echoes the best practices guidelines put forward in 2018 by the ABFO which caution
980 that conclusions regarding bitemark linkage should only exclude or not exclude a dentition as
981 having made the bitemark. Stronger terms regarding matching or conclusive identification are
982 not condoned by the ABFO or the thinkshop participants.

KEY TAKEAWAY #4.5: As reflected in research studies to date, bitemark examiners may not agree on the interpretation of a specific bitemark, including whether the injury is a bitemark, the features present, and the exclusion or non-exclusion of potential biters.

5. Conclusions/ Future of Bitemark Analyses

5.1. Research Needs

Calls have been made for empirical studies to assess the limitations of bitemark analysis for decades. Since 1960, those in the bitemark community have been highlighting the lack of empirical research and the need to address reliability concerns in bitemark methods (Table 5.1). These calls have largely gone unheeded.

This report examined publicly available literature and information pertaining to bitemark analysis. Forensic bitemark analysis lacks a sufficient scientific foundation because the three key premises of the field are not supported by the data. First, human anterior dental patterns have not been shown to be unique at the individual level. Second, those patterns are not accurately transferred to human skin consistently. Third, it has not been shown that defining characteristics of that pattern can be accurately analyzed to exclude or not exclude individuals as the source of a bitemark. The data available does not support the accurate use of bitemark analysis to exclude or not exclude individuals as the source of a bitemark. If the field seeks to advance, the key takeaways provided in this report are starting points for areas needing improvement, not an exhaustive list of specific shortcomings.

KEY TAKEAWAY #5.1: Repeated calls for additional data by critics and practitioners (since at least 1960) suggest insufficient support for the accurate use of bitemark analysis and a lack of consensus from the community on a way forward.

Table 5.1. Previous statements on lack of scientific foundations for bitemark analysis

#	Reference Citation	Statement
1	Fearnhead 1960	"Apart from a few isolated places research in forensic odontology is non-existent…[after discussing results from an experiment he performed] I do not wish to overstate the importance of this experiment, but I do hope that it serves to illustrate the need for a more critical awareness by the legal profession and those concerned in forensic science of the danger of accepting, too readily, evidence which at first sight appears to be based on an exact science. This awareness can only come through the dissemination of knowledge from the sciences, which, in turn, can only be obtained through researches." "…evidence which involves the identification of a person by tooth-marks left as bruises in flesh should never be admitted, and evidence involving bite-marks in, for example, foodstuffs should be examined extremely critically."

#	Reference Citation	Statement
2	DeVore 1971	"…once the skin has been excised, the shrinkage is so great and so irregular as to make its value for identification of bite marks extremely doubtful."
3	Barbenel & Evans 1974	"…we are still ignorant of the conditions during normal biting and hence considerable research is needed into this before simulation studies can be considered of real clinical and forensic relevance."
4	Rothwell 1995	"There is no consensus on the appropriate technical methods for evaluating the bite mark and potentially associated dental composition." "Above all, the investigator should recognize the innate problems in bite mark examination and avoid expanding the analysis beyond rational boundaries." "Forensic dentists need to approach bite marks with a certain degree of skepticism and continually acknowledge their limitations."
5	Pretty & Sweet 2001	"From this review of the literature, it is possible to state that the issue of skin distortion in bitemark analysis has not been fully addressed and the cautions issued by DeVore [see row #2 above in this table] and others should still be heeded today."
6	Senn 2007	"…good intentions are no substitute for scientific thoroughness… Pretty and Sweet's 2001 words still ring true in 2006…'Despite the continued acceptance of bitemark evidence in European, Oceanic and North American Courts, the fundamental scientific basis for bitemark analysis has never been established' (Pretty & Sweet 2001). Although there have been efforts and concern by forensic odontologists in the area of bite mark analysis, the body of knowledge verified by research, the demonstratable level of expertise proven by proficiency testing, and the establishment and enforcement of standards and ethics are seriously lacking. These failures are a profound detriment to the professional standing of forensic odontology." "The conclusion by anyone that one person *in an open population* can be said to have created a bite pattern on human skin with reasonable certainty cannot be scientifically supported." (emphasis in the original)
7	National Academy of Sciences committee (NRC 2009)	The scientific basis of these methods was "insufficient to conclude that bitemark comparisons can result in a conclusive match"

#	Reference Citation	Statement
		"A standard type, quality, and number of individual characteristics required to indicate that a bitemark has reached a threshold of evidentiary value has not been established."
8	Franco et al. 2015	"Based on the performed systematic review, the uniqueness of human dentition was not scientifically proven. Specifically, the lack of (1) a power analysis for the stratification and size calculation of the studied sample, (2) intra- and inter-examiner calibrations, (3) advanced 3D data registration, (4) automated landmarking, (5) validated 3D shape comparison software, and (6) statistical methods and quantifications for data comparison present the main limitations in the studies aiming to prove the uniqueness of human dentition."
9	Texas Forensic Science Commission 2016	"The Commission recommends that bitemark comparison not be admitted in criminal cases in Texas unless and until the following are established: (1) *Criteria for identifying when a patterned injury constitutes a human bitemark.* This criteria should be expressed clearly and accompanied by empirical testing to demonstrate sufficient inter and intra-examiner reliability and validity when the criteria are applied…" (emphasis in the original)
10	Reesu & Brown 2016	"If bite mark analysis is to continue…forensic odontologists would do well to bolster the research base behind their methodology in forming opinions on bite marks." "There are differences in opinions between forensic odontologists when considering the same case involving a bite mark. Furthermore, forensic odontologists as individuals changed their opinions when looking at the same case after a wash-out period…Opinions on bite mark evidence should be treated with caution, further research done, and introduction of a recognized system for both validation/revalidation."
11	PCAST 2016	"…bitemark analysis does not meet the scientific standards for foundational validity, and is far from meeting such standards. To the contrary, available scientific evidence strongly suggests that examiners cannot consistently agree on whether an injury is a human bitemark and cannot identify the source of bitemark with reasonable accuracy."

#	Reference Citation	Statement
12	Bowers 2019	"…clearly recognize the facts of weak foundational science, absence of empirical proofs, dependence on group acceptance as a substitute for validity, and resulting damaging effects to the criminal justice system..." "The tide against its continued use can be summed up in succinct terms: • A lack of valid evidence to support many of the assumptions and assertions made by forensic dentists during bite-mark comparisons. • Error rates by forensic dentists are perhaps the highest of any forensic identification specialty still being practiced. • Bitemark testimony has been 'introduced in criminal trials without any meaningful scientific validation, determination of error rates, or reliability testing.'"

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6. References

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