



A systematic review of 3D scanners and computer assisted analyzes of bite marks: searching for improved analysis methods during the Covid-19 pandemic

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Abstract

The global Covid-19 pandemic has forced forensic dentists to improve infection control methods. This search investigated the practical utilization of different 3D scanners to record and to analyze bite marks in the skin- and inanimate objects with this aim in mind. A systematic review of the literature using keywords like “human bite mark”, “bite mark analyzes”, “3D analyzes”, “3D scanning”, “forensic odontology”, and “forensic dentistry” was performed in three scientific databases: MEDLINEovid®, Pubmed® and Google Scholar. The initial search yielded 263 full-text articles, of which 15 were considered eligible and current within the last 10 years. 3D scanners and computer-assisted human bite mark analyzes showed potential advantages and can be effectively used in forensic odontology on skin and inanimate objects. These technologies minimize the number of people being exposed to pathogens, simplify the chain of evidence, facilitate immediate information exchange between the team members and enable the virtual presentation of the expert witnesses in a court of law.

Keywords Forensic science · Forensic odontology · Covid-19 · 3D documentation · Photogrammetry · 3D computer-assisted analyzes · Bite marks

Introduction

Covid-19 has presented new challenges in every sphere of life including the science of bite mark analysis. The pandemic has seen an increase in the number of domestic violence cases, murders, cases involving sexual assault, child abuse, and the neglect of the elderly [1–4]. Human bite marks were observed in many of these cases [5].

Currently collecting evidence for bite marks poses a risk of occupational exposure to Covid-19 infection for the forensic dentist in a mortuary setting, particularly if the necessary precautionary measures are lacking [6, 7]. The use of alternative methods, such as three-dimensional (3D) scanning technology which are less invasive, digitally transferrable, and equally accurate to

conventional methods should now be considered. Since the onset of Covid-19, the Pretoria team of forensic odontologists have included 3D scanning of both, the bite marks and the suspect’s dentition in their analysis of the relevant cases. Bitemarks will always undergo a degree of warpage, shrinkage, and distortion with time [8–10]. A 3D scan is thus, a representation of a distorted bite mark [11] in either skin or an inanimate object. A 3D scan is a snapshot in time that will capture and freeze the images that we know are already distorted. A 3D scanner generates point clouds from geometric data gathered from the surface of an object. The object’s shape is reconstructed from the digital data on the known spatial position of each measurement point. Different scanning and processing software programs are used to generate comparison of dental casts and scanned dentition [12].

This systematic review aims to investigate the practical utilization of different 3D scanners in recording bite marks in skin- and inanimate objects and the use of computer-assisted methods in human bite mark analyzes during and after the Covid-19 pandemic.

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Methods

In August 2020, during the height of the South African pandemic, a systematic review of the literature was performed using an online search in three scientific databases: MEDLINE@, Pubmed@, and Google Scholar. As a result of rapid development of technology, only articles from 2011 onwards were considered relevant. Key words such as “human bite mark,” “bite mark analyzes,” “3D analyzes,” “3D scanning,” “forensic odontology,” and “forensic dentistry” were searched. The search was expanded by checking the reference lists of the articles. Additional mining of above mentioned databases was conducted in February 2021 for the purpose of this review. The articles obtained by the search were screened and selected by two operators. Only English language full-text articles with indexed abstracts published in ISI-accredited dental, forensic, and legal medicine journals were included. Short communications, letters to the editor, case reports, ordinary, and systematic reviews were excluded from the results.

From the articles that fulfilled the criteria, the following data were extracted: (1) the aim of the study, (2) the sample size, (3) the bite mark substrate (4) registration techniques and the scanners used, (5) software, and (6) the study outcome.

Results

The initial search yielded 263 full-text articles, of which 248 did not meet the selection criteria. A PRISMA[13] flowchart is presented in a Fig. 1.

The year of publication, authors, titles, and journals are presented in the Table 1.

Fifteen eligible articles were divided on a basis of the analysis target as follows:

- A Studies assessing the reliability of measurements of different 3D scanners are presented in the Table 2 (6 articles)
- B Studies utilizing 3D comparison of the dental crown morphology of the anterior dentition are presented in the Table 3 (3 articles)
- C Studies on suitability of different computer-assisted methods for bitemark analyzes are presented in the Table 4 (6 articles)

Discussion

From the search it became clear that 3D digital scanning of bite marks enables accurate and fast recording of the bite marks in soft substances such as cheese, chocolate, pears, apples, and human skin without further distortion of the evidence during impression taking [10, 11]. While using digital

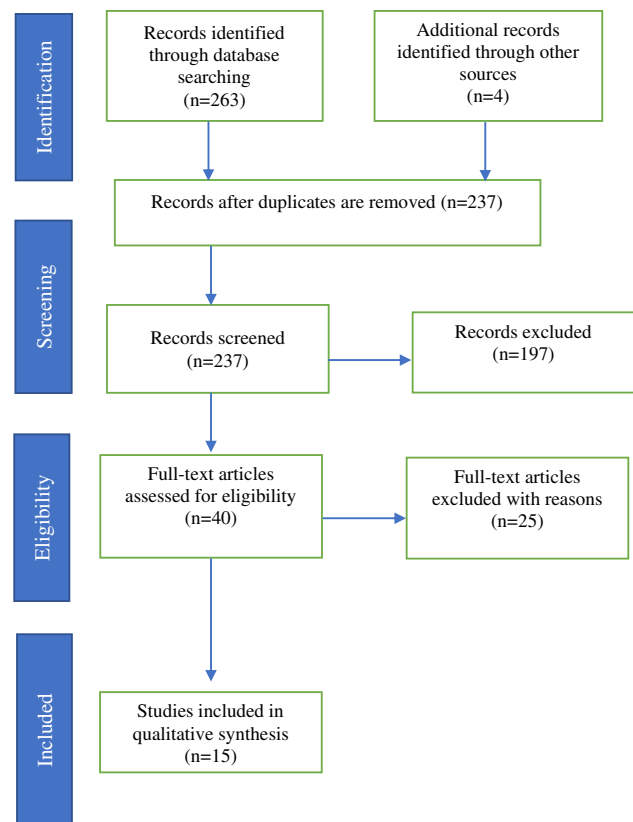


Fig. 1 Flow diagram of the search and selection process [13].

scanners, an exposure to pathogens can be minimized and several steps can be eliminated. These include mixing an impression material, waiting for setting of impressions and casting of models from impressions [27]. Taking impressions of the suspect’s dentition can sometimes be problematic due to noncompliance and gagging which can be alleviated by the small heads available in some of the scanners [28, 29]. Maintaining a chain of evidence becomes far simpler and can be digitally traced. A digital file can be uploaded to a cloud server for immediate communication with the forensic team members [30]. It minimizes the number of people being exposed to the evidence or suspect from a pandemic control point of view and allows the team to work remotely via cloud server. It also enables for the virtual presentation of the expert witness in a court of law [31].

Studies assessing the reliability of different 3D scanners

The study on contact 3D scanners showed that the contact between the scanner and the bitemark was problematic as the evidence could inadvertently be damaged. Contact scanners were also unable to capture surfaces with marked concavity

Table 1 Studies included in this systematic review

Year	Author	Title	Journal
2012	Naether <i>et al.</i> [10]	The examination and identification of bite marks in foods using 3D scanning and 3D comparison methods	Int J Legal Med (2012) 126:89–95
2014	Martin-de-las-Heras <i>et al.</i> [14]	A quantitative method for comparing human dentition with tooth marks using three-dimensional technology and geometric morphometric analysis	Acta Odontologica Scandinavica. 2014; 72: 331–336
2015	Molina <i>et al.</i> [12]	Accuracy of 3D Scanners in Tooth Mark Analyzes	J Forensic Sci. (2015), 60, S1 S222-226
2015	Przystańska <i>et al.</i> [15]	The Effectiveness of 2D and 3D Methods in the Analysis of Experimental Bite Marks	Dent. Med. Probl. 52, 1 (2015), 86–92
2016	de Sainte Croix <i>et al.</i> [16]	Three-dimensional imaging of human cutaneous forearm bite marks in human volunteers over a 4 day period	Journal of Forensic and Legal Medicine 40 (2016) 34–39
2017	Chong <i>et al.</i> [17]	A Pilot Study to Analyze the Uniqueness of Anterior Teeth Using a Novel Three-dimensional Approach	Journal of Forensic Identification. 2017; 67(3):361–78
2017	Franco <i>et al.</i> [18]	Uniqueness of the anterior dentition three-dimensionally assessed for forensic bitemark analysis	Journal of Forensic and Legal Medicine 46 (2017) 58–65
2017	Franco <i>et al.</i> [19]	Three-dimensional analysis of the uniqueness of the anterior dentition in orthodontically treated patients and twins	Forensic Science International 273 (2017) 80–87
2017	Rajshekar <i>et al.</i> [20]	The reliability and validity of measurements of human dental casts made by an intra-oral 3D scanner, with conventional hand-held digital calipers as the comparison measure	Forensic Science International 278 (2017) 198–204
2018	Ali <i>et al.</i> [21]	Analysis of Intercanine Distance and Dimensional Changes in Bite Marks on Foodstuffs Using Cone Beam Computed Tomography	The American Journal of Forensic Medicine and Pathology 1(2018)
2018	Corte-Real <i>et al.</i> [22]	Tri-dimensional pattern analysis of foodstuff bite marks — A pilot study of tomographic database	Forensic Science International 288 (2018) 304–309
2019	Fournier <i>et al.</i> [23]	Three-dimensional analysis of bite marks using an intraoral scanner	Forensic Science International 301 (2019) 1–5
2019	Ramos <i>et al.</i> [24]	A new method to geometrically represent bite marks in human skin for comparison with the suspected dentition	Australian Journal of Forensic Sciences 51 (2019) Issue 2
2020	Fournier <i>et al.</i> [25]	Three-dimensional analysis of bite marks: A validation study using an intraoral scanner	Forensic Science International 309 (2020) 110,198
2020	Molina <i>et al.</i> [26]	Dental parameter quantification with semiautomatized computational technology for the analysis of human bite marks	Australian Journal of Forensic Sciences (2020) 1–11

[12]. This has led to increased interest in noncontact methods such as laser scanning. The 3D laser scanners have proved their precision for different applications. However, the difficulty detecting sharp edges, especially incisal edge of the anterior incisors may provide false presentation of the tooth morphology. While using the 3D laser scanners for dental casts and biting edges in practical forensic cases, the margin of the error should be considered [12].

Utilization of fringe pattern projection scanners, also known as optical surface scanners such as Gom ATOS III (Gom, Braunschweig, Germany) in 3D documentation of bite marks was reported in two articles [10, 15]. The method is noninvasive, displays high resolution results, and does

not damage the evidence [10]. The difficulties of capturing tiny areas and deep structures of the surface and the cost of equipment have been reported in the literature [10, 32].

The evidence suggests that intra- and inter- arch measurements obtained from digital dental models using intraoral scanners is equivalent to dental plaster models or digital images generated from conventional dental impressions [33]. Zfx IntraScan intraoral 3D scanner and its virtual measuring tool was found valid for measuring key features in dental casts [20]. The studies done by Fournier *et al.* [23, 25] proposed a protocol for the bite-mark analyzes using Planmeca Emerald® intraoral scanner. In a validation study it was found reliable on wax, cheese, and chocolate, but yielded

Table 2 Overview of the studies on the reliability of different 3D scanners

Author	Molina et al. [12]	Rajshekar et al. [20]	Fournier et al. [25]	Fournier et al. [23]	Ali et al. [21]	Corte-Real et al. [22]
Aim of the study	Comparison of contact and laser 3D scanners in tooth mark analysis	Assesses measurements accuracy made on dental casts using intra-oral 3D scanner	Assess the 3D bite mark analysis protocol using an intraoral scanner	Study the feasibility of a 3D bitemark analysis protocol using an intraoral scanner	Assess bite marks dimensional changes on foodstuffs at different time intervals using CBCT	Comparison a foodstuff and the suspects' dentition through the analysis of tomographic images
The sample size	10 individuals 20 casts	25 individuals 50 casts	27 individuals	16 casts 24 bitemarks	30 individuals 60 casts 120 bitemarks	12 individuals 12 bitemarks
Substrates used generating bitemark	None	Human skin	Dental wax Cheese Chocolate Apple	Dental wax Cheese	Cheese Chocolate Apple	Apple
Registration technique	2020i Desktop scanner Picza® 3D Scanner	Zfx™ Intra Scan + Handheld Caliper Mitutoyo® Digimatic	Planmeca Emerald®	Planmeca Emerald®	Kodak 9000 C 3D	iCAT
Software packages	Meshlab V1.3.3 3-D, Pisa, Italy) Convector© Dentalprint©	Zfx™ IntraScan software	Romexis® 5.1.0R Cloudcompare® 2.9.10.1 MeshMixer® 3.4.35	Romexis® 5.1.0R Cloudcompare® 2.9.1 MeshMixer® 3.4.35	Kodak Digital image communication software, SPSS 17.0	InVivo5™ SPSS Statistics 20 Micro-soft Excel

Table 3 Overview of studies utilizing 3D comparison of the dental crown morphology of the anterior dentition

Author	Chong <i>et al.</i> [17]	Franco <i>et al.</i> [18]	Franco <i>et al.</i> [19]
Aim of the study	<i>Use intraoral 3D scanner and 3D analyzes software to investigate the uniqueness of the anterior human dentition (UHD) among patients who had completed orthodontic treatment. Determine the feasibility of a combined intraoral 3D scanner and 3D analyzes software approach to bite mark analyze</i>	<i>Assess the UHD in the anterior dentition based on systematically reducing the 3D quantity of dental material analyze and using slices of the analyzed dental material</i>	<i>Prove the UHD 3D comparing the dental crown morphology of the anterior dentition in of orthodontically treated patients, twins, and orthodontically treated twins in relation to a threshold sample of identical dentitions</i>
The sample size: Individuals	20 individuals 44 casts	445 casts	445 casts
Substrates used generating bitemark	none	none	none
Registration technique	3MLava Chairside Oral Scanner C.O.S. (3 M ESPE St. Paul, MN)	XCAD 3D® (XCADCAM Technology®, Sao Paulo, SP, Brazil)	XCAD 3D® (XCADCAM Technology®, Sao Paulo, SP, Brazil)
Software packages	Meshlab V1.3.2, Pisa, Italy) Geomagic Control (Morrisville, NC)	Geomagic Studio® (3D Systems®, Rock Hill, SC, USA) software package (GS), S.® 8.0 (Tibco®, Palo Alto, California, USA)	Geomagic Studio® (3D Systems®, Rock Hill, SC, USA) software package (GS), S.® 8.0 (Tibco®, Palo Alto, California, USA)

the poorest results in apples. The use of any type of scanner and associated equipment always requires a high degree of training and expertise. These devices showed an excellent potential for use in bite-mark analysis.

The CBCT-assisted analysis of bite marks was considered a nondestructive, accurate, and simple. Ali *et al.* [21] concluded that CBCT images of bite marks displayed no distortion artifacts and enabled accurate 3D measurements. Corte-Real *et al.* [22] showed in their study that bite mark analysis could be done through software that searches for matching dentitions in a CBCT database. This could add value in the identification process of potential suspects where countries have one or more national databases for all the performed radiographic images. Using ionizing radiation may pose potential risk to the operator and the suspect [34]. This obviously does not apply to the bitemarks on the bodies observed and investigated in the mortuary. The availability of the CBCT machines and the cost of the procedure might be an obstacle for utilizing this novel approach in less developed countries. In spite of these shortcomings, CBCT could provide a potential alternative modality for recording the bite marks in forensic odontology, especially on food-stuffs [35].

Photogrammetry in 3D documentation of skin bite marks was published for the first time in 2003 by Thali *et al.* [36]. A series of overlapping photos from different points of view around a targeted object are taken and the 2D photographs are combined into a true-to-scale 3D model of the object. Simplicity, inexpensiveness, free software, and somewhat

trivial technical requirements of photogrammetry enable us to create a textured 3D surface model [37]. The accuracy of this technique has been proven to be comparable to the laser scanners [38]. Photogrammetry has been routinely utilized in forensic 3D documentation of skin injuries [39–41]. The use of photogrammetry was demonstrated by De Sainte Croix *et al.* [16] in our systematic review.

Studies utilizing 3D comparison of the dental crown morphology of the anterior dentition.

The uniqueness of human dentition (UHD) could be assessed using 2D (flatbed scanning and photography) and 3D (laser scanning and intraoral scanning) image registration [42]. Chong *et al.* [17] used intraoral 3D scanner and 3D analyzes software to investigate the UHD in the orthodontically treated study population on human anterior dentition. The authors found that anterior dentition was unique within their study population as no perfect matches were detected. They concluded that using 3D scanner and commercially available 3D analyzes software were highly encouraging methods in bite-mark analyzes particularly in the absence of any positive DNA assay [17]. In two studies by Franco *et al.* [18, 19] they investigated the uniqueness of the human dentition utilizing 3D methods in randomly selected subjects. The subjects included orthodontically treated patients and twins to increase the reliability of the study [18]. The first study analyzing incisal edges did not show uniqueness, but when

Table 4 Overview of the studies on computer-assisted methods for bite mark analyzes

Author	Naether et al.[10]	Martin-de-las-Heras et al. [14]	Przystańska et al.[15]	de Sainte Croix et al.[16]	Ramos et al. [24]	Molina et al.[26]
Aim of the study	Evaluate the identification of bite marks in different kinds of food and investigated whether the identification of the biter is still possible, after food has been lying around for some time	Develop a quantitative method to compare 3D overlays from dental casts with experimental bite marks by using geometric morphometric analysis	Investigate the possibility of identifying a biter using 2D and 3D analysis of experimental bite marks	Investigate if a 3D imaging technique, creating a 3D time-lapse image of a bite mark can provide context to the nature and location of injury	Can BitePrint calculate the same parameters for the biting edges generated from 3D images of dental casts?	Determine dental parameters that characterize human bite marks and dentitions for biter identification using semi-automated technology
The sample size	6 adults	13 upper and lower dental casts and corresponding simulated bite marks	10 individuals	10 individuals 10 bite marks	64 casts 16 photos of bite marks	65 individuals 18 photos of bite marks
Substrates used generating bite mark	Buttered bread Apples, Chocolate Cheese	Dental wax	Cheese Chocolate Apple Grapes	Human skin	Piglet skin	Human skin Piglet skin
Registration technique	3D optical surface scanner GOM Atos III (Braunschweig, Germany)	3D contact-type scan (Roland, Picza 3D, Pix-3, Roland DG Corp, Japan)	Epson Perfection 4900 GOM Atos II Rev.01, Canon 20D SLR camera	DI3D® Photogrammetry	Photographs, non-specified equipment	2020i Desktop 3D scanner Photographs, non-specified equipment
Software packages	ATOS 3D Studio max animation software	DentalPrint® Dig v. 2.10 morphometric Software (Stony Brook, 2006) SPSS-Windows 15.0 (SPSS Inc., Chicago, IL)	CorelDrawX3 ATOS	Autodesk Maya 2015® Adobe Photoshop® CS6 Adobe After Effects CS6®	C+ + with the Microsoft Visual Studio 2005 PE, QGLViewer, OpenGL Dentalprint© Biteprint© SPSS Windows 20.0 (SPSS Inc., Chicago, IL)	Dentalprint© Biteprint© SPSS Statistics 20

the complete crowns of the anterior teeth were included, UHD was demonstrated [18, 19].

It must be understood that the presence of recognizable dental features, nicks, chips, and imperfections are required to correctly match suspects to bitemarks. A lack of features seen in orthodontically treated patients, especially in skin bite cases will create problems in identifying a perpetrator and be impossible to present in the court of law [9].

After considering the research results 3D scanners and computer-assisted methods in bite mark analyzes showed promising results. Small sample size, lacking statistical methods for data comparison, missing intra- and inter-examiner calibrations, nonvalidated software for 3D shape comparison or relatively scarcity of studies performed *in vitro* present the main limitations in studies included.

Studies on computer-assisted methods for bitemark analyzes

Computer-assisted methods for bitemark analyzes enable experts to work remotely and seek advice from the other team members and colleagues during pandemic. It must be noted, that computers cannot manufacture that which does not exist. Digital analyzes of the bite mark can only enhance existing features and enable the proficient presentation of these features. The use of 3D imaging technology offers practical advantages to the courtroom, specifically with respect to the juror's understanding of technical language [31].

Biting is a dynamic process. Thus, bite mark analysis is based on a combination of morphological and positional data [43]. Computer assisted graphics and animations have showed the potential for accurate representation of bite marks in all three dimensions, compare the dentitions of presumed biter to the evidence and match the corresponding biter to the bite-mark among several suspects [44]. ATOS software enables an automatic computation of the deviation between the two meshes, thus, allows an easy and very accurate analysis and interpretation of the results. 3D Studio Max software allows dynamic comparison during the animated act of biting, where 3D match or nonmatch is clearly detectable [10].

De Sainte Croix *et al.* [16] successfully created 3D time-lapse animations, which can be viewed on most electronic devices. The quality of DI3D Photogrammetry system was accurate enough to enable the animations to illustrate the color and shape of bruising. Some distortions were present around the edges of 3D model. The animations can have significant benefit to the photographic evidence presentation in court setting, especially if the presentation has been made virtually [16].

Realistic 3D perspective allows the placement of a higher number of landmarks [44, 45]. Additionally, automated image superimposition and mesh processing leads to improved digital 3D image analyzes and interpretation of bitemarks [18]. 3D capture of the bitemark and digital analysis provide images that have less angular and perspective distortion, which results in less measurement errors [24]. It can be performed using high-tech commercially available as well as special forensic odontology software such as Dentalprint©, BluePrint©, and Biteprint© [12, 24, 26].

Semiautomated BluePrint© software enables the investigator to compare the photographs of a bite mark with the biting edges of a dental cast. It generates data on the dental parameters required for identification (e.g. intercanine distance, rotation, eccentricity, angular position, and distance to the arch of each tooth mark). BitePrint© represents the biting edges of dental casts as a set of geometric coefficients, offering a measurable, semiautomatic, and less subjective analysis. Molina *et al.* [26] evaluated the accuracy and reproducibility of dental parameters between photographs of bite marks and dental casts using semiautomated technology. The sensitivity of this technology was found to be 92% and specificity 53%. The accuracy of these programs can be applied in practical forensic dentistry and in criminal trials involving human bite mark cases [24, 26].

Conclusion

The global pandemic has forced us to search for new and innovative techniques which are safer to use in our day to day practice of forensic science. Three-dimensional scanners have shown potential advantages and can be used in forensic odontology on the skin and inanimate objects. The analyzes of the bite marks depends on quality, quantity, and the presence of recognizable features in a pattern associated analysis. The latter requires only a degree of accuracy which is standard in the majority of 3D scanners. Training and expertise on 3D scanners and computerized technologies is an absolute prerequisite for forensic dentists to obtain accurate results. The authors believe that in changing world the 3D scanning and analyzing techniques will replace the methods which were derived in a world free of Covid-19, Ebola, HIV, and global connectivity.

Authors contribution Both authors contributed to the idea for the article, Piret Vilborn performed the literature search and drafted the work, which was approved by both authors. Both authors commented on previous versions of the manuscript, read and approved the final manuscript.

Declarations

Ethical approval Not applicable.

Conflict of interest The authors declare no conflict of interest.

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