Optical Coherence Tomography for Quantification of Wear in Dental Restorative Materials

By

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Abstract

Tooth enamel is the hardest substance in the body, comprising approximately ninety-six percent mineral. It has an average Vickers hardness of 283 and an average elastic modulus of 1.3 GPa. Despite these excellent mechanical properties, wear is unavoidable due to the harsh oral environment. The wear rate of a healthy tooth in a fair and well-maintained oral environment ranges between 10-40 μm per year, but in most cases, it exceeds these values. Tooth wear is an irreversible gradual loss of dental hard tissue and can be grouped into two major categories: a) Mechanical (attrition, abrasion, and abfraction), and b) Chemical (erosion). It is crucial to study and quantify the progression of tooth wear because macro wear (visible to the naked eye) can severely affect individuals' eating rate and habits. Anything that affects human health is of great research interest. In most cases, damaged enamel is restored to regain functionality using materials such as amalgam, composite, ceramics, or other restorative materials. Unfortunately, the wear rates of these materials far exceed those of natural teeth.

Clinically, dentists use more complex techniques for wear detection, involving several steps such as impressions of the oral cavity, cast reproduction, and microscopic analyses. These techniques are time-consuming, expensive, and not 100% accurate. Therefore, researchers have proposed using Optical Coherence Tomography (OCT). OCT is an imaging technique used in various medical fields and has proven to be the most clinically viable alternative to dental X-rays. However, no study has tested the use of OCT to

measure tooth wear without the assistance of depth (length) measuring apps like Screen Ruler, ImageJ, etc.

To address the aforementioned problems, we first conducted a systematic review of the global prevalence of tooth wear to estimate the percentage of people affected by tooth wear (with dentine exposure). Following a search strategy and eligibility criteria, we synthesized 22 clinical studies conducted from 1984 to 2020. The overall estimated prevalence of tooth wear was 38% (95% CI: 31–46%). Our meta-analysis revealed that the regional (continental) subgroup was responsible for the high percentage heterogeneity in the included studies. We also used Bhattacharyya Distance (BD) to examine the similarities between the studies in the subgroups. Our results showed that studies from Africa were distinct from others, while studies from Europe, America, and Asia shared some similarities.

Secondly, cost is one of the significant setbacks preventing OCT from becoming a widely used dental imaging tool. We built our OCT system with an inexpensive nonlinear laser source and compensated for the nonlinearity using an image reconstruction method that utilized redundant and non-uniform (scaled-NDFT) samples. We used the system to image human teeth and compared the results with images reconstructed using the standard FFT image reconstruction method. Our results showed that images reconstructed with the scaled NDFT method had a higher peak signal-to-noise ratio (PSNR).

Lastly, we explored the possibility of using OCT to quantify tooth wear without the assistance of any length/depth measuring apps. We started by measuring emulated wears in a restorative material (amalgam) and comparing the results with the standard method (Surface Profiler). We then used OCT to compare emulated wears in three different restorative materials. The results from the first part showed excellent agreement between the depth measurements obtained from the two methods, and Bland-Altman plots revealed a significant systematic difference between the two measuring methods. The OCT measurements deviated by a few microns, and the difference in means between the two methods was not statistically significant. Furthermore, the results from the second part were analyzed using one-way ANOVA and Tukey's post hoc tests.

In conclusion, our results showed that OCT is one step closer to being fully adopted as a clinical imaging tool in dentistry.

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Dedication

To my parents, Waheed Azeez and Taibat Azeez, who may not be literate but possess a deep love for education. I am grateful for their unwavering support and encouragement.

To my brothers, sisters, friends, and colleagues for their constant support throughout this journey.

To my beloved "generals," Imran and Ilyas Azeez, for their love and support.

Contributions of Authors

Dr. Rodrigo França: Conceptualized the project, reviewed and submitted manuscripts for publications, and supervised the project.

Dr. Sherif Sherif: Contributed to the design and implementation of the research and reviewed the manuscripts.

Mr. Akeem Azeez: Performed the experiments, conducted statistical analyses, and wrote the manuscripts. He is the main contributor to this thesis.

This thesis is written in a "sandwich" format and consists of seven chapters. Chapter I serves as the introduction, Chapter II presents a review validating our research hypothesis, Chapter III focuses on the systematic review of the global prevalence of tooth wear in permanent dentition, and Chapter IV discusses the image reconstruction method used in this work. Chapter V provides details on the sample preparation steps and our custom wear machine. Chapter VI presents the article on the quantification and comparison of wear in dental restorative materials. Finally, the last chapter concludes the thesis and provides recommendations for future works.

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Chapter I- Introduction

Motivation

Tooth wear is the gradual loss of enamel due to chemical and/or physical attack [1]. It can be categorized into four types: abrasion, erosion, attrition, and abfraction. Tooth wear is influenced by various factors, including mechanical, chemical, biological, and tribological aspects, making its study challenging [2]. In some cases, worn teeth become more sensitive to temperature, leading to discomfort while eating. Severe tooth wear can extend to the pulp chamber, compromising the tooth's integrity and affecting the patients' food choices, potentially threatening their well-being [3].

The first motivation for this project stems from the fact that tooth wear prevalence has been extensively studied by researchers worldwide, but each study reports different prevalence rates. Consequently, the global prevalence of tooth wear remains unknown. Therefore, there is a need to statistically synthesize all these studies to determine the overall prevalence of tooth wear. Previous systematic reviews on this subject have certain limitations. In 2010, Kreulen et al. [4] conducted a systematic review focusing solely on permanent dentition and used age as the basis for the meta-analysis of included studies. In 2015, Salas et al. [5] conducted a systematic review of erosive wear prevalence in children and adolescents (aged 8-19), neglecting other age groups and types of tooth wear.

Furthermore, due to the complexity of tooth wear, dentists often find it challenging to track the micro-progression of tooth wear since it becomes detectable only after a substantial amount of tooth structure has been lost. The current clinical procedure for wear detection involves taking impressions of the teeth using impression materials like alginate, elastomeric materials, or impression plaster. These impressions are used to create positive casts in the laboratory, which are then used for wear measurements using veneer calipers or other measuring devices. However, this procedure is time-consuming, and the results are unreliable and inaccurate.

To overcome the limitations of the current procedure, researchers have proposed using Optical Coherence Tomography (OCT) to quantify and monitor the progression of tooth wear. However, the cost of OCT has been a barrier to its widespread adoption as a clinical tool in dentistry. Thus, the second motivation of this project is to develop an affordable OCT system for dental imaging. To achieve this, we designed our OCT system using an inexpensive low-linearized laser source and supported it with an image reconstruction method (scaled NDFT). This method utilizes redundant and non-uniform sample data to compensate for the non-linearity of the laser source, eliminating the need for expensive high-linearized laser sources to obtain high-quality OCT image reconstructions.

The third motivation arises from the fact that most previous attempts to use OCT for enamel thickness or tooth wear measurements relied on other length or depth measuring apps/software. For example, Hara et al. quantified enamel thickness using OCT by measuring the depth of enamel from the Dentine-Enamel Junction (DEJ) with ImageJ after 3D image reconstruction. Their results showed that OCT measurements were significantly higher on average by 0.064 mm compared to the standard method [6]. Podoleanu et al. used OCT in conjunction with ImageJ to measure volume loss in teeth samples due to dental abfraction and attrition [7]. Additionally, Hara et al. employed cross-polarization OCT with the aid of Microsoft ScreenRuler to evaluate enamel wear progression [8], and they relied on JR ScreenRuler by Spadix software to measure demineralization severity on the enamel [9]. However, the drawback of these methods is that OCT cannot accurately measure wear in homogeneous materials such as restorative materials since it relies on the spatial distance between dentin and the point of interest on the enamel for wear quantification. Furthermore, OCT results often differ by several millimeters compared to standard methods, limiting the widespread application of OCT in dental clinics.

Goals and Objectives

The overall goal of this study is to utilize Optical Coherence Tomography (OCT) to quantify wear without relying on any length or depth measuring apps, thereby advancing OCT's potential as a clinical imaging tool in dentistry.

The specific objectives of the study are as follows:

1. Conduct a systematic review to ascertain the global prevalence of tooth wear in permanent dentition.
2. Determine the most effective image reconstruction method for dental imaging.
3. Calibrate the OCT using data obtained from a standard depth measuring device.
4. Perform a statistical comparison between the results obtained from the two depth measuring devices.
5. Utilize OCT exclusively to compare the wear rates in three different restorative materials.

Thesis organization

This thesis comprises seven chapters. The first chapter introduces the motivations and objectives of the thesis. In the second chapter, a comprehensive review is conducted on the various technologies and equipment that researchers have employed to quantify tooth wear in dentistry. This chapter equips us with the necessary information to understand the attempts made and challenges faced by numerous researchers in studying wear in dentistry.

The third chapter presents a systematic review of the global prevalence of tooth wear in permanent dentitions, which is essential in providing information about the percentage of the world's population experiencing severe tooth wear (Objective 1). Chapter four focuses on the image reconstruction method employed in this work (Objective 2). Chapter five addresses sample preparation and provides details about our custom-wear machine.

Chapter six describes how we calibrated and used OCT to quantify wear in a restorative material (Amalgam) and how OCT was solely used to compare wear in three different restorative materials—Amalgam, Low-viscosity composite, and High-viscosity composite (Objectives 3-5). Additionally, this chapter includes the complete literature review for the thesis.

The final chapter summarizes the thesis and includes a discussion on future related projects.

Conflicts of interest

The authors have no conflicts of interest.

Ethical approval of our experiment

No ethical approval is needed for this work.

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Chapter II- Quantification of Tooth Wear in Dentistry: A Review

Synopsis

This chapter discusses the technologies and techniques that researchers have employed in order to develop a clinical tool for quantifying tooth wear. This discussion is necessary to establish the background work that will validate or invalidate our research hypothesis, which states that there is currently no clinical tool available for quantifying tooth wear in dentistry.

Abstract

Objectives: This work aims to review the technologies that researchers have used to quantify tooth wear as part of the process of developing a viable clinical tool for monitoring the progression of tooth wear.

Methods: An electronic search was conducted on five different databases (Medline, Scopus, Embase, ScienceDirect, and Web of Science) using predetermined inclusion and exclusion criteria.

Results: The search strategy yielded 140 articles, and after applying our eligibility criteria, only 23 articles were included in this review.

Conclusions: This review demonstrates that researchers have made significant advancements in providing a clinical tool for quantifying tooth wear. Although there are currently some limitations preventing the widespread clinical use of these innovations, continued efforts in this field hold the potential for a breakthrough in the near future.

Introduction

Tooth wear (TW) is the gradual loss of enamel due to mechanical and chemical factors [1][2]. If left untreated, it becomes an irreversible process that can progress from the enamel down to the tooth pulp, leading to dentinal hypersensitivity and severe pain. TW is typically more prevalent in adults as it progresses with age, but it has become more noticeable in younger populations due to increased consumption of acidic food or drinks [3][4].

Severe TW, which exposes the dentin, requires the use of restorative materials to restore tooth functionality. Unfortunately, these restorative materials wear out faster than the enamel they replace, resulting in frequent patient visits to the dental clinic. Therefore, the goal is early diagnosis and preventive interventions to reduce the rate of enamel loss.

In clinical practice, dentists rely on visual inspection and X-rays to detect tooth wear, but these methods have limitations. Visual inspection is subjective, inconsistent, and heavily dependent on the experience of the inspector. Furthermore, it is challenging to visually detect early wear progression. X-rays provide information on wear activities by showing the contrast between the enamel and the pulp, but they are not capable of detecting wear at its early stages.

Visual inspection is based on a scoring system that assigns an ordinal score to each tooth based on its level of wear. The Tooth Wear Index (TWI), developed by B.G. Smith and Knight in 1984[5], is one of the prominent scoring indices, assigning the highest value to teeth with exposed dentin.

Researchers have employed various techniques and equipment to quantify tooth wear in laboratory settings. This review article aims to present previous studies on the quantification of tooth wear, including their limitations and advancements. It serves as a guide for active researchers working towards developing novel equipment that can be used clinically to track and monitor tooth wear.

Methods

(a) Inclusion criteria

The inclusion criteria were developed in line with the PICOS; the following criteria were excluded from the search: animal studies and case reports.

Table 1. Inclusion criteria

Population	Any age or sex with tooth wear;
Intervention	Measurement of the tooth wears using any technology or device.
Comparison	Not applicable
Outcome	Quantification of tooth wear
Study design	Longitudinal, prospective, in-vitro, in-vivo and comparative.

(b) Literature Search

An electronic search was conducted on five different research databases (Medline, Scopus, Embase, ScienceDirect and Web of Science) using the combination of the search terms: [("tooth wear" OR "dental wear") AND ("measurement" OR "quantification")]. We evaluated the studies for inclusion and exclusion criteria, and only relevant studies that are fit for this review were included (Table 1).

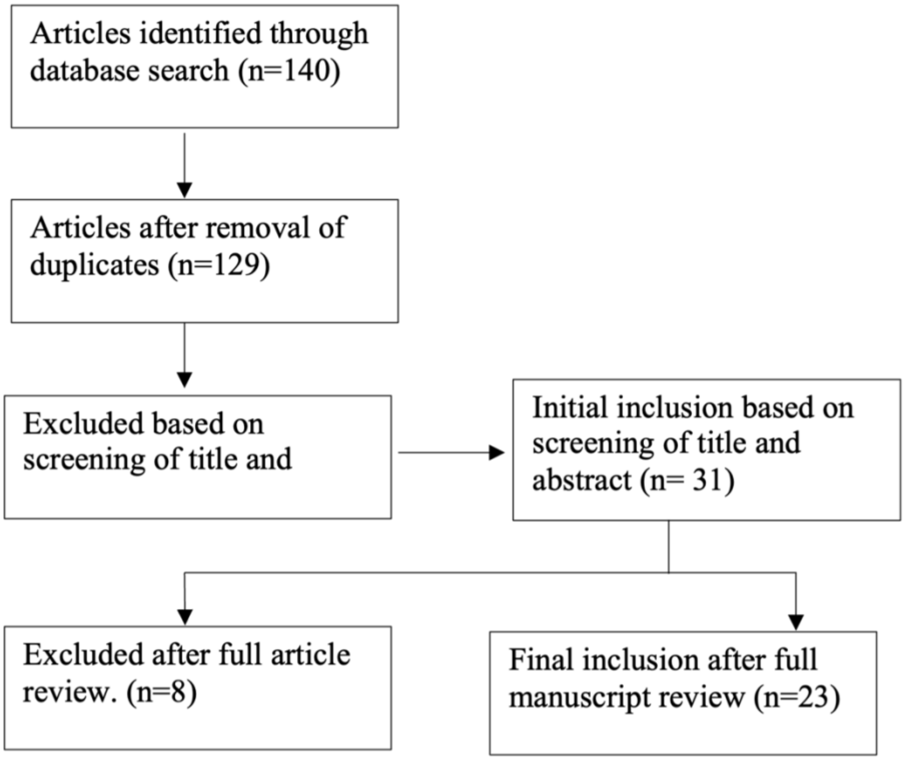

Figure 1. Search strategy flow chart

Results

Following the search strategy flow chart in Figure 1, twenty-four studies were included in this review (Table 2).

Table 2. Included studies

Number	Author	Year of Publication	Method for quantifying wear.	Study design	Conclusion
1.	R.G. Chadwick et al. [6]	1997	Computer-controlled mapping device for scanning electro-	Comparative	The Digitally Train Model (DMT) generated by the mapping device

			conductive dental cast.		appeared to match results from visual inspections.
2.	R. Hickel et al. [7]	1997	A reference-free 3D optical scanner that uses the principle of triangulation to generate images of the dental cast with the aid of 3D superimposition software.	1-3 years longitudinal study.	The system could detect wear with an accuracy of 10 μm.
3.	R.S. Dwyer-Joyce et al. [8]	2005	Ultrasound	Comparative	Good correlation between the Ultrasound techniques and direct measurement of sectioned teeth.
4.	S.D. Heintze et.al[9]	2006	Profilometry device, FRT MicroProf optical sensor and 3D laser scanning device	Comparative	Good agreement between the three quantification methods.
5.	M.K. Etman et.al[10]	2008	Superimposition of images	Longitudinal	Experimental hot-pressed ceramic and metal-ceramic systems showed less wear

					compared to Procera AllCeram.
6.	A. Theocharopoulos et al. [11]	2010	White light profilometry.	Comparative	Good agreement between the two different software used in the quantification of wear.
7.	M.K. AL-Omiri et al. [12]	2010	CAD-CAM Laser scanning machine	Comparative	Measuring the dies of worn dentition directly gives more accurate results than measuring it from images obtained from a digital machine.
8.	N. Koottathape et al. [13]	2012	Digital CCD microscope	Comparative	All tested materials except microfilled composite showed low surface wear when the poppy seed was used as a medium in the three-body wear emulation. However, it

					is the contrast when the materials were exposed to PMMA as a third medium in the three-body wear emulation.
9.	D. Tantbirojn et al. [14]	2012	Optical scanner	Longitudinal	Tooth wear in patients with GERD was significantly higher than in the control group.
10.	N. Koottathape et al. [15]	2012	Contact profilometry and CCD microscopy	Comparative	Both measuring methods were equally suitable for quantifying wear.
11.	T.M Wilwerding et.al [16]	2013	Non-contact profilometer	Comparative	Significant wear difference between the resin composites materials.
12.	M.K. Al-Omiri et.al[17]	2013	CAD-CAM Laser Cercon System, tool maker microscope	Longitudinal, Comparative	The two methods were able to detect the wear

					progression effectively.
13.	C. Mann et.al[18]	2014	3D confocal microscopy, environmental scanning electron microscope	Comparative	Both methods were able to detect early erosive wear.
14.	A. Algarni et al. [19]	2016	µ-Computed Tomography and Optical Coherence Tomography	Comparative	High agreement between the two measuring methods.
15.	B.Kim et.al [2]	2017	Quantitative light-induced fluorescence	Comparative	Significant correlation between the fluorescence intensity of the teeth and grinding depth.
16.	A. Grau et al. [20]	2018	Optical laser scanner & Laser scanning microscope	Comparative	Satisfactory agreement between the two measuring methods. Significant wear difference between the tested materials.

17.	C. Stöckl et al. [21]	2018	Laser scanner	Comparative	Ceramic restorative material showed better wear-resistant than composite resins.
18.	S.K. Kim et al. [22]	2019	Quantitative light-induced fluorescence	Comparative	The value of the fluorescence difference using the QLF showed a strong correlation with the enamel thickness and the severity of the tooth wear.
19.	H.S. Lee et al. [1]	2019	Quantitative light-induced fluorescence	Comparative	The dentine exposure is significantly dependent on the difference in fluorescence intensity.
20.	Y. Nakamura et al. [23]	2019	High-speed optical microscope	Comparative	Tooth wear was affected by the porcelain surface roughness and not by the hardness.

21.	B. Korkut et al. [24]	2020	Ultrasound, digital radiography, FluoreCam and colorimeter	Longitudinal	All the measuring methods showed the capability to monitor tooth wear progression, but the ultrasound provides more reliable and repeatable results.
22.	S.K. Kim et al. [25]	2020	Quantitative light-induced fluorescence (QLF)	Comparative	The QLF was able to detect dentine exposure in worn teeth and could be used to determine pathological tooth wear in posterior teeth.
23.	M. Bas et al. [26]	2021	Handheld intraoral scanner in conjunction with 3D topographic measuring technique.	Comparative	The measuring technique provides an opportunity to quantify the wear in children since it does not rely on dentine exposure.

Discussion

Several studies have examined the quantification of wear in dentistry using different measuring methods. Based on our database search, R.G. Chadwick et al. conducted the first research on this topic in 1997[6], when the team developed a mapping device for the assessment of wear in both tooth and restorative materials. To quantify the wear in the tooth replicas, they used an algorithm to detect the matching and differences between the generated Digital Terrain Models (DTMs) for the tooth replicas. They used the mapping device to scan electroconductive tooth replicas and evaluated its accuracy in assessing the thickness of four engineers' slip gauges. They recorded the overall mean error of the mean thicknesses to be 4.4 μm. The limitation of their measuring method is the need to have an electroconductive replica of the teeth before mapping can be done. Besides, they rely on a commercial software package to generate the tooth surfaces, which could introduce errors in the wear measurement.

The same year, A. Mehl et al. [7] developed a 3D optical scanner to measure wear in restorative materials. They evaluated the accuracy and precision of the device by measuring wear in Gypsum replicas of restored teeth through triangulation meshing methods using free automated 3D superimposition software with and without reference positions. Their results showed that the device's precision and accuracy depend on the replicas' surface inclination. If the reference positions of the replica before and after wear could be matched, the precision could be as low as 2.2 μm; otherwise, it could be higher.

The limitation of their study is similar to R.G. Chadwick et al. because they also rely on a free automatic matching program for wear measurement.

Based on our search, R.S. Dwyer-Joyce et al. [8] reported the first twenty-first-century research on the measurement of wear in dentistry. The team used ultrasound to measure wear in human teeth. They employed three different ultrasonic techniques to measure wear in the enamel of extracted teeth. The first method was based on time of flight with a focusing immersion transducer (25 MHz), while the other two techniques used planar probes (10 MHz), one with a time-of-flight approach and the second with a resonance method for quantifying wear in the enamel. They then compared the results from all the techniques with direct measurement of the sectioned teeth. Their findings showed that the contact probes method was the easiest to set up, and the time-of-flight approach provided the most accurate results. They concluded that all three methods exhibited a correlation with the direct method measurement. The only limitation of their procedure is the fact that they used ultrasound technology, which is slower in acquiring data compared to optical technology.

Additionally, in 2020, B. Korkut et al. [24] designed a longitudinal study where they utilized ultrasound, FluoreCam, colorimeter, digital radiography, and cast-model analysis to evaluate the clinical progression of incisal wear over four years. Their results demonstrated that ultrasound is the most reliable and repeatable method for clinically monitoring incisal wear progressions below 10 μm, followed by FluoreCam. Clinically, the colorimeter was more efficient in monitoring wear that is 40 μm or greater, while digital radiography could not detect progressive incisal tooth wear.

S.D. Heintze et al. [9] in 2006 compared three different in vitro wear quantification methods for dental restorative materials. The wear measurement devices used were a profilometer, an optical sensor (FRT MicroProf), and a 3D laser scanning device. To quantify wear, the researchers utilized matching software for the profilometer and the 3D laser scanning device, while the optical sensor used white light to determine the depth in the prepared samples.

Their results demonstrated excellent agreement between the three wear measuring methods, with an intraclass correlation coefficient of 0.99 for the variable volume loss and 0.94 for the variable vertical loss. They concluded that all three devices were suitable for wear quantification, but in terms of speed, the laser scanning device outperformed the others.

In 2008, S. Dunne et al. [10] conducted a two-year longitudinal study to measure tooth and ceramic wear using a superimposition technique in three different ceramic systems: experimental hot-pressed ceramic, Procera AllCeram, and metal-ceramic. Data was collected at six-month intervals, and dye was applied to highlight changes in the replicas before scanning with a non-contacting laser profilometer. A 3D surface modeling software was employed to generate the occlusal surfaces of the replicas. Subsequently, the images were superimposed using mathematical fitting software (Scan-Surf) to quantify the wear progression.

The researchers concluded that the Procera AllCeram-enamel system exhibited more wear compared to the other two systems. However, a limitation of their procedure is the use of superimposition software, as there may be some errors when aligning the anatomically stable occlusal areas, thus potentially impacting the accuracy of the measurements.

T.J. Clifford et al. [12] conducted a study in 2010 using a new CAD-CAM laser scanning machine in conjunction with a toolmaker's microscope to detect incisal tooth wear over six months. The researchers compared the results obtained from this method with the conventional tooth wear index. The CAD-CAM machine was used to scan and print digital images of the stone dies prepared from each participant's tooth. These printed images were then examined under the toolmaker's microscope to quantify wear. The microscope was also used to directly assess the dies. To measure the difference between the images taken before and after wear, the toolmaker's microscope utilized X and Y micrometers attached to its stage. The results from the microscope were compared with the results obtained from the Smith and Knight clinical tooth wear index (TWI).

The researchers concluded that the wear measurement results obtained from the digital images were more precise, while the results from directly measuring the dies were more accurate. Furthermore, the conventional method (TWI) was found to be the least sensitive and often failed to detect wear progression. Three years later, M.K. Al-Omiri et al. [17] utilized the methodology proposed by Clifford et al. to investigate tooth wear in the upper anterior teeth of fifty participants. Their results demonstrated that both the toolmaker's microscope and direct digital measurement were capable of tracking wear progression in the upper anterior teeth, with the toolmaker's microscope providing the most accurate results. However, a limitation of their proposed wear quantification method is that it can only be applied in vitro settings.

In 2010, M. Cattell et al. [11] utilized a white light profilometer to generate digital images of human molar cusps and glass-ceramic discs before and after in vitro wear emulation. The researchers employed software (Proform, Scantron, UK) to superimpose the images for wear quantification. Additionally, they employed another software (Proscan-2000) to further process the superimposed images by removing interferences and isolating the worn areas before conducting the wear measurement. The two results were then compared. The researchers concluded that the accuracy of their mean height loss measurement results significantly improved when the worn areas were isolated. A limitation of this study is similar to that of Y. Aoyagi et al. [15], who investigated and compared wear emulation on composite resin using a contact profilometer and 3D imaging with a digital charged couple device (CCD) microscope. They concluded that the volume wear loss and maximum depth produced by both methods were linearly correlated ($r2 > 0.97$; $p < 0.01$); however, the CCD method required less time to complete. A limitation of their study is that the specific steps taken for wear quantification were not explicitly stated. Additionally, W. Finger et al. [13] employed the same technology to investigate two and three-body wear of three different types of composite resins: microfilled, micro-hybrid, and nano-hybrid. The researchers validated the accuracy of the CCD microscope by comparing the results of a Rockwell indentation on a polished CoCr-alloy and two composite resin surfaces to those obtained using a traveling microscope at 50-fold magnification. Their results demonstrated that the microfilled composite exhibited the highest abrasive wear under the three-body wear simulation with poppy seed slurry.

R. Delong et al. [14] used an optical scanner to study the effect of gastroesophageal reflux disease (GERD) on 12 participants and compared them with six control participants at baseline and after six months. The researchers employed an optical scanner with a lateral resolution of 60 µm and an accuracy of 5 µm to scan dental stone replicas of the participants' teeth. They then utilized software (Cumulus by Regents of the University of Minnesota) to align the baseline and six-month digital images for wear quantification. Their results revealed that participants with GERD exhibited higher tooth surface loss compared to the control participants. One limitation of this study is that the researchers did not validate the wear results obtained through the software using a standard clinical method.

C. Mann et al. [18] utilized a 3D confocal microscope and an environmental scanning electron microscope to quantitatively and qualitatively investigate enamel surfaces for erosive wear. They exposed the enamel surfaces to different pH levels (1.5 and 3.0) for durations of 30s, 60s, and 120s. Their results demonstrated that the pH values and duration of exposure influenced the roughness of the enamel surface.

Based on our search and inclusion criteria, the first report of wear quantification using optical coherence tomography (OCT) was presented by A. Algarni et al. [19] in 2016. For wear quantification using PS-OCT and μ-CT, the researchers employed ImageJ software to measure the distance between the enamel and the Dentin-enamel junction (DEJ) in the 3D reconstructed images by drawing a perpendicular line from the enamel to the DEJ. They then compared the enamel thickness measurements obtained from polarization-sensitive OCT (PS-OCT) with those from microcomputed tomography (μ-CT) and histology. The researchers observed that the PS-OCT measurements were significantly higher than the μ-CT and histology measurements by 0.064 mm and 0.088 mm, respectively. However, there was no significant difference between the μ-CT and histology measurements. Their results also revealed a high level of agreement among the three methods. A limitation of their study is the reliance on ImageJ software for quantifying tooth wear.

S.-K. Kim et al. [2] conducted research in 2017 to explore the potential of using quantitative light-induced fluorescence (QLF) for detecting tooth wear. This technology relied on the difference in autofluorescence intensity between the enamel and dentin when exposed to ultraviolet light. The researchers employed Swept-Source Optical Coherence Tomography (SS-OCT) to identify the enamel contour closest to the Dentin-Enamel Junction (DEJ). They then gradually ground the tooth in increments of 100 μm until the dentin was exposed. Fluorescence and OCT images were captured after each grinding step, and ImageJ software was utilized to calculate the fluorescence intensity by measuring the brightness (grey value) on the 8-bit grayscale fluorescence images. The results indicated a strong correlation between the maximum brightness (MB) values of the fluorescence images and the grinding depth ($r2 = 0.994$, $p < 0.001$). The study had two limitations: 1. The precision of the digital caliper used for measuring the grinding depths was not stated. 2. The researchers relied on ImageJ software to calculate the maximum brightness of the fluorescence images for quantifying wear. Two years later, the researchers [22] employed the same technology to estimate the residual enamel thickness in teeth with varying degrees of occlusal wear. They compared the QLF wear measurements (difference between the fluorescent intensities of the sound and worn surfaces) with the conventional tooth wear index (TWI) and enamel thickness measurements obtained from cross-sectioned teeth surfaces using a stereomicroscope and an interlaced camera. The results revealed a negative correlation between the QLF wear measurements and the residual enamel thickness, but they showed a strong correlation with TWI (Spearman rho = 0.753, $p < 0.001$). In 2020, they utilized the QLF technology to differentiate between enamel and dentin-exposed wear in clinical images [25], and presented optimal cut-off values for fluorescent intensity values corresponding to wear. Receiver Operating Characteristic (ROC) curve analysis was employed to determine the optimal cut-off values. The results indicated that the optimum cut-off values for anterior and posterior teeth were 12.1 and 14.7, respectively, while the corresponding areas under the ROC values were 0.86 and 0.93.

C. Stöckl et al. [21] utilized a laser scanner in conjunction with a function developed in R statistics software to examine the macrotopographical volume loss of CAD-CAM composite resins subjected to 2- and 3-body wear emulation. They also employed a scanning electron microscope to investigate the microtopography of the resin surfaces. For wear estimation, they identified two separate Regions of Interest (ROI) on the specimens, namely ROI (inside) and ROI (outside). In R, multiple regression and numerical integration were employed to model the geometric properties of ROI (outside), and the predicted values for ROI (inside) and residuals were calculated. The volume loss was estimated by subtracting the reference residual from the original scan images. The results indicated distinct wear patterns for both 2-body and 3-body wear. Additionally, A. Grau et al. [20] validated the reliability of the R statistics function developed by C. Stöckl et al. for quantifying tooth wear when they used it to estimate wear in two composite resins and compared the results with those obtained using a confocal laser scanning microscope system. The results demonstrated a good agreement between the two methods, with a reliability of 98.5%.

Y. Nakamura et al. [23] utilized a high-speed optical microscope to investigate abrasive wear between human enamel and three different porcelain materials, aiming to determine the effects of hardness, surface roughness, and crystal structure of the porcelain materials on enamel wear. The microscope was used to calculate the height of enamel wear by subtracting the measured length of the enamel test piece after the abrasive test from the original measured length. The volume loss on the enamel was calculated geometrically. Additionally, a surface roughness meter was employed to quantify wear on the porcelain materials. Vickers hardness and X-ray diffraction tests were conducted on the porcelains. The results revealed that enamel wear was not dependent on the hardness of the porcelain but rather on the surface roughness. One limitation of their research is that in vitro dental research results hardly represent what would occur in the oral environment.

M. Bas et al. [26], in 2021, used a handheld intraoral scanner in conjunction with a proposed 3D topographic measurement technique to evaluate dental microwear in deciduous and permanent molars of children. They obtained two measurements from the scanner's mesh files: 1. The relative flat surface area as a percentage of the occlusal surface

(RFSA%) and 2. The mesial interior slope angle (MISA). These measurements were compared with the TWI wear scores for the same set of teeth. The results indicated that measurements from both methods aligned with the qualitative TWI scores and correlated with age. However, RFSA% was deemed unreliable in monitoring the progression of wear after dentine exposure. The researchers concluded that the measurement of MISA is more suitable for studying wear in children. The limitations of their technique are that: 1. They relied on software like ImageJ for the measurements of MISA. 2. The data acquisition process is time-consuming.

Conclusion

This review highlights the different equipment, technology, and techniques that researchers have utilized to quantify tooth wear, along with their limitations. Quantification of tooth wear remains an active research area in dentistry. Considering the level of effort demonstrated in this review, it is expected that in the near future, clinical equipment will be developed to enable dentists to effectively track and measure tooth wear.

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Chapter III- Statistical Estimation of wear in permanent teeth: A systematic review

Synopsis

This chapter discusses the prevalence of tooth wear in permanent teeth through a systematic review on the topic. Such an examination is crucial for establishing a global estimate of the percentage of individuals affected by tooth wear. The review was published in the Dentistry Review-Journal in November 2021 with the DOI: 10.1016/j.dentre.2021.100001. The authors of the review are Akeem A. Azeez, Sherif Sherif, and Rodrigo França.

Abstract

Objectives: An up-to-date quantitative assessment of the prevalence of tooth wear, specifically with dentine exposure, in the permanent dentition is lacking. The purpose of this systematic review was to synthesize clinical studies and research related to tooth wear to derive an overall estimate of its prevalence in the permanent dentition.

Data/sources: The eligibility criteria for this work included population-based studies that reported the prevalence of tooth wear in permanent teeth among adolescents and adults aged 12 to 80 years. Following these criteria, an electronic search of databases including Medline, Scopus, Embase, Science Citation Index, and Biosis (Web of Science) was performed from 1984 to 2020. Data regarding sample size, geographical locations, year of

publication, age, etc., were extracted from each study to determine the overall estimated prevalence of tooth wear. Meta-regression analysis was used to identify the sources of heterogeneity in the studies, while Bhattacharyya Distance (BD) was used to investigate the relationship within the sources of heterogeneity.

Study selection: The search strategy identified 4,205 studies, and after removing duplicates (959), conducting title and abstract screening (3,206), and full-text reading (60), a total of 22 studies comprising 20,112 subjects were included in the systematic review. The overall estimated prevalence of tooth wear was found to be 38% (95% CI: 31-46%). Subgroup meta-analysis revealed that the geographical location of the publications (continents/regions) was responsible for the variability in the prevalence of tooth wear among the included studies, with Europe having the lowest prevalence rate. Bhattacharyya Distance (BD) analysis highlighted that studies from Africa were notably different from other studies, while studies from Europe, America, and Asia showed some similarities.

Conclusions: This study demonstrated that the prevalence of tooth wear with dentin exposure was 38%, with significant heterogeneity among the included studies, primarily influenced by the geographical location of the studies.

Clinical significance: The results of this study can serve as an informative guide for clinicians and policymakers to understand the global prevalence of tooth wear. This information can contribute to the formulation of policies aimed at reducing the occurrence of tooth wear.

Introduction

Teeth are the hardest substances in our bodies, serving the primary function of chewing food. They also play a significant role in speech production and personal appearance [1]. An adult human has thirty-two sets of teeth, which can be categorized into four types: incisors, canines, premolars, and molars. Tooth enamel, the hardest substance in the human body, naturally wears at a minimal rate of only 10-40 μm per year. In contrast, most dental restorative materials have a wear rate of 8-9 μm per month. This significant difference in wear rates makes it challenging to fully substitute enamel with artificial restorative materials [2]. Consequently, there is a concerted effort among researchers to comprehensively understand wear and its causes to develop suitable enamel replacements.

Wear is defined as the gradual loss of material from contacting surfaces due to relative motion between the surfaces of interest [3,4]. Tooth wear (TW) refers to the gradual reduction in enamel thickness caused by oral environments, dietary factors, and other non-carious or non-traumatic factors [5]. TW is influenced by various biological and chemical factors, many of which are beyond the control of dentists or researchers. This complexity makes the study of TW challenging as substance loss on the tooth surface can be attributed to multiple wear mechanisms and factors.

The global prevalence of TW remains unknown. Extensive studies on the prevalence of different types of TW have been conducted worldwide, with reported prevalence rates varying from 7% [6] to 84% [7]. The variation in reported TW prevalence can be attributed to differences in geographical locations, sample sizes, indices used to assess wear, specific types of TW investigated, age groups, and other factors. Therefore, a comprehensive examination of all studies on this topic is needed. Although two systematic reviews on TW prevalence have been published by different authors [8,9], there are some limitations in their reviews. For instance, Kreulen et al. [9] only performed subgroup analyses based on age, and the second systematic review solely estimated the prevalence of erosive tooth wear in children and adolescents (8–19 years old). Furthermore, both studies were conducted in 2010 and 2015, respectively, while numerous clinical studies investigating the prevalence of tooth wear have been published since then.

This study aims to provide an extensive systematic review of literature on all types of tooth wear in permanent dentitions, including their prevalence and etiologies. The objectives of this study are to: (1) estimate the overall global prevalence of TW, (2) determine the factors contributing to variations in reported prevalence across studies or subgroups using meta-regression analysis, and (3) utilize Bhattacharyya Distance (BD) to analyze the relationships between subgroups responsible for the variation in the included studies.

Methods

(a) Inclusion and exclusion criteria

This review adhered to the established guidelines of Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA), and the eligibility criteria were based on the PICOS framework (Participants, Intervention, Comparison, Outcomes, and Study design). The authors of the included papers conducted comparative studies on the prevalence of tooth wear with dentin exposure among specific age groups, examining factors such as diets, environmental conditions, and habits that contribute to wear. The inclusion and exclusion criteria are summarized in Table 3. Dentine exposure served as an indicator of the severity of tooth wear in all the studies included in this review.

The protocol for this systematic review was registered and published on PROSPERO (International Prospective Register for Systematic Reviews) with the publication ID CRD42020144835.

Table 3. Eligibility criteria for the systematic review

Domain	Inclusion criteria	Exclusion criteria
Participants	• Human population (adolescents and adults) between 12-80 years. • Have a considerable number of teeth (either child or adult) • Any gender and nationality	Infants (or less than 12 years old) and elderly participants with dentures (gum-mouthed persons)
Intervention	Examination of tooth wear as evaluated by known\popular wear indices. Only the following wear indices will be considered • O'Brien • TWI by Smith and Knight, • Lussi • O'Sullivan • Ordinal • BEWE	Use of unknown or uncommon wear index
Comparisons	Not Applicable	
Outcomes	Major patterns/categorizations as a result of clinical evaluation/classification of the participants' teeth using certain wear indices.	
Study design	Any type of population-based study design that involve comparative studies of tooth wear in a healthy representative sample. • Longitudinal cohort studies • Case-control studies • Cross-sectional studies	• Animal studies • Non-comparative studies • Quasi-Experimental/randomized control trials for tooth wear or other treatments • reviews. • Meta-analyses • Letters to editor

(b) Information sources and search strategy

Medline, Scopus, Embase and Science Citation Index and Biosis (Web of Science) were searched from 1984 till 2020. Smith and Knight developed the first standard wear index in 1984[10,11], so the year was used as the start year for the search. English language limit (and study design filter) was also applied. Hand searching by identifying relevant papers in ScienceDirect and citation searching forward to establish a body of publications for inclusion.

(c) Study selection

The databases were searched using MeSH terms and other keywords in combinations presented in table 3 below. The selection of the articles was done by two reviewers (AA and RF) who independently assessed the title and abstract of the selected articles based on the inclusion criteria. Disagreements were resolved by discussion or by the involvement of the third reviewer (SS).

(d) Data collection and data items

The same two reviewers independently extracted details-including the name of the first author, year of publication, geographical location of research, the sample size of subjects, percentage of male/female, type of data source, type of dentition, type of wear present in the subjects, wear index, number of examiners and the number of teeth observed-from each paper (see Table 4 for the abridged data).

Table 4. Search keywords used on different databases.

Database	Search strategy	Hits
Scopus	(TITLE-ABS-KEY (((tooth OR teeth OR dent*) W/5 (wear* OR erosion OR abrasion OR abfraction OR attrition)))) AND (TITLE-ABS-KEY (((tooth OR teeth OR dent*) W/3 (permanent OR deciduous OR temporary OR baby OR primary)))) AND (LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013) OR LIMIT-TO (PUBYEAR , 2012) OR LIMIT-TO (PUBYEAR , 2011) OR LIMIT-TO (PUBYEAR , 2010) OR LIMIT-TO (PUBYEAR , 2009) OR LIMIT-TO (PUBYEAR , 2008) OR LIMIT-TO (PUBYEAR , 2007) OR LIMIT-TO (PUBYEAR , 2006) OR LIMIT-TO (PUBYEAR , 2005) OR LIMIT-TO (PUBYEAR , 2004) OR LIMIT-TO (PUBYEAR , 2003) OR LIMIT-TO (PUBYEAR , 2002) OR	1570

	LIMIT-TO (PUBYEAR , 2001) OR LIMIT-TO (PUBYEAR , 2000) OR LIMIT-TO (PUBYEAR , 1999) OR LIMIT-TO (PUBYEAR , 1998) OR LIMIT-TO (PUBYEAR , 1997) OR LIMIT-TO (PUBYEAR , 1996) OR LIMIT-TO (PUBYEAR , 1995) OR LIMIT-TO (PUBYEAR , 1994) OR LIMIT-TO (PUBYEAR , 1993) OR LIMIT-TO (PUBYEAR , 1992) OR LIMIT-TO (PUBYEAR , 1991) OR LIMIT-TO (PUBYEAR , 1990) OR LIMIT-TO (PUBYEAR , 1989) OR LIMIT-TO (PUBYEAR , 1988) OR LIMIT-TO (PUBYEAR , 1987) OR LIMIT-TO (PUBYEAR , 1986) OR LIMIT-TO (PUBYEAR , 1985) OR LIMIT-TO (PUBYEAR , 1984)) AND (LIMIT-TO (LANGUAGE , "English"))	
Web of Science	(((((tooth OR teeth OR dent*) Near/5 (wear* OR erosion OR abrasion OR abfraction OR attrition)))) AND ((((tooth OR teeth OR dent*) Near/3 (permanent OR deciduous OR temporary OR baby OR primary)))))) Refined by: PUBLICATION YEARS: (2020 OR 2010 OR 2001 OR 1992 OR 2018 OR 2009 OR 2000 OR 1991 OR 2017 OR 2008 OR 1999 OR 1990 OR 2016 OR 2007 OR 1998 OR 1989 OR 2015	394

	OR 2006 OR 1997 OR 1988 OR 2014 OR 2005 OR 1996 OR 1987 OR 2013 OR 2004 OR 1995 OR 1985 OR 2012 OR 2003 OR 1994 OR 1984 OR 2011 OR 2002 OR 1993) AND LANGUAGES: (ENGLISH)	
Medline	1 exp Tooth Wear/ (5900) 2 ((tooth or teeth or dent*) adj5 (wear* or erosion or abrasion or abfraction or attrition)).tw,kf. (7563) 3 dentitions, permanent/ (1714) 4 Tooth, Deciduous/ (11845) 5 ((tooth or teeth or dent*) adj3 (permanent or deciduous or temporary or baby or primary or adult or milk or secondary)).tw,kf. (24832) 6 3 or 4 or 5 (29610) 7 1 or 2 (10751) 8 6 and 7 (637) 9 limit 8 to (english language and yr="1984 -Current") (536) 10 exp Animals/ not (exp Animals/ and Humans/) (4610034) 11 9 not 10 (495)	495
Embase	1.tooth disease/ (30185) 2. ((tooth or teeth or dent*) adj5 (wear* or erosion or abrasion or abfraction or attrition)).tw,kw. (7696) 3. secondary dentition/ (543) 4. deciduous tooth/ (9837) 5. ((tooth or teeth or dent*) adj3 (permanent or deciduous or temporary or baby or primary or	1746

	adult or milk or secondary)).tw,kw. (23664) 6. 3 or 4 or 5 (27020) 7. 1 or 2 (34987) 8. 6 and 7 (3215) 9. limit 8 to yr="1984 -Current" (2916) 10. exp Animals/ not (exp Animals/ and Humans/) (13261404) 11. 9 not 10 (1746)	

Total= 4205
Total After removal
of duplicates = 3246

(e) Statistical Analysis

The global prevalence of tooth wear was determined by combining data from studies that reported wear prevalence in the same type of dentition. The Random Effects model, also known as the effect size, was chosen for estimating the global prevalence because it accounts for the expected variation in true tooth wear prevalence across studies due to participant diversity [12]. The amount of heterogeneity in the studies was assessed using the Restricted Maximum-Likelihood estimator (REML), known for its relatively small bias and high efficiency [13].

Meta-regression analysis and subgroup meta-analysis were employed to identify the sources of heterogeneity among the studies. The Bhattacharyya distance (BD) [14] was used to examine potential relationships between studies within categories or clusters. Subgroups within each category were assumed to follow a joint Gaussian distribution, and the BD provided insights into the similarities or differences in populations based on lifestyle, diets, or geographical locations. A smaller BD indicates similarities between populations, while a larger BD suggests differences. To evaluate the presence of publication bias, the funnel plot and Egger's test were utilized. All statistical analyses were performed using the meta and dmetar packages in R, which are available through The Comprehensive R Archive Network (CRAN) [14,15].

Results

The literature search of the databases yielded 4,205 articles, which were reduced to 3,246 after removing duplicates. The initial screening involved assessing the titles and abstracts of the articles, resulting in the exclusion of 3,206 articles. The remaining 40 articles underwent a full-text reading, and an additional 20 articles were included based on their references (refer to Figure 2). A total of 60 articles were thoroughly reviewed, and out of these, 38 articles were excluded. Among the exclusions, 16 papers were removed because they utilized uncommon tooth wear indices not specified in the eligibility criteria, while the remaining papers were excluded for various reasons (see Table 5).

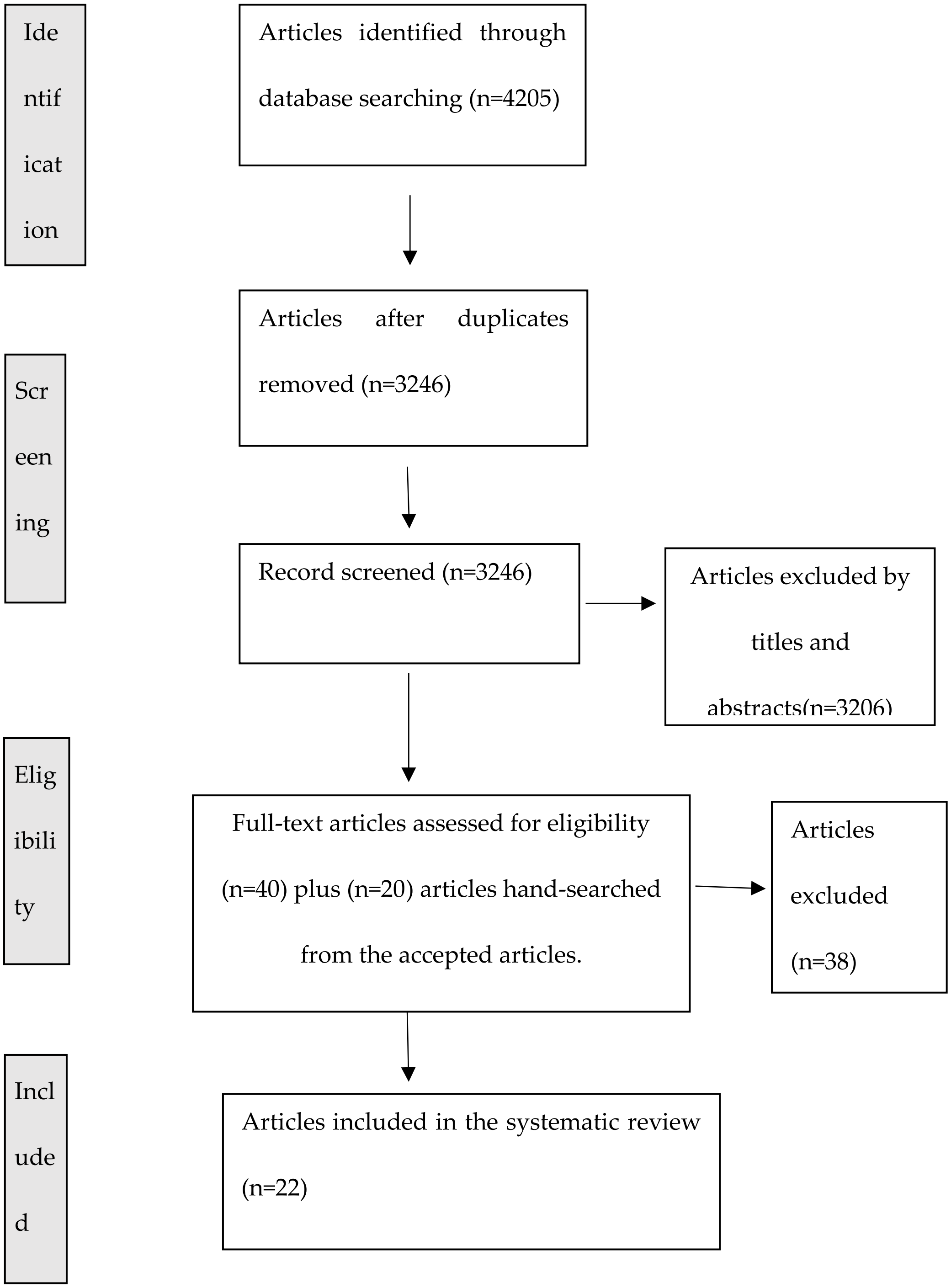


Figure 2. Search strategy flow chart.

Table 5. Excluded studies

Authors	Year	EXCLUSION REASONS
Jed. S. Hand et al. [16]	1987	Dentate participants
Seligman. D. A et al. [17]	1988	In-vitro study
N. Alamoudi [18]	1999	Full-text not accessible.
Ogunyinka.A et.al [19]	2001	Uncommon wear Index
Ganss. C et.al [20]	2001	wrong study design
K. M. Ayers et al. [21]	2002	Type of wear not stated
A. K. Johansson et al. [22]	2002	Prevalence of tooth wear not stated
M. I. Al-Malik et al. [23]	2002	wrong population
T. Jaeggi et al. [24]	2004	Uncommon wear Index
A. Milosevicet al.l [25]	2004	Uncommon wear Index
R. Daniela et al. [26]	2007	Type of wear not stated
S. Kazoullis et al. [27]	2007	Uncommon wear Index
Carvalho Sales-Peres et.al [28]	2008	Type of wear not stated
Cunha-Cruz. J et.al [29]	2010	Type of wear not stated
Mulic. Aida et.al [30]	2010	Uncommon wear Index
Wild. Y. K et.al [31]	2011	Not healthy participants
Ibiyemi. Olushola et.al [32]	2012	Uncommon wear Index
Raza. M. et al. [33]	2012	Uncommon wear Index
Paschos. E et.al [34]	2013	foreign language
Fung. A et.al [35]	2013	Type of wear not stated
Moimaz. S. A et al. [36]	2013	Uncommon wear Index
Farahmand. Fatemeh et.al [37]	2013	Unhealthy participants
Isaksson. H. et.al [38]	2013	Wrong population & Uncommon wear Index
De Carvalho Sales-Peres et.al [39]	2013	Uncommon wear Index
Nakane. Ayako et al. [40]	2014	Wrong population
Holbrook. W. P et al. [41]	2014	Unhealthy participants
Hasselkvist. Agneta et.al [42]	2016	wrong study design
De Andrade. Francisco J.P et.al [43]	2016	Uncommon wear Index
Li.Mary. H. M.et al.l [44]	2016	Dentate participants
Al-Ashtal. Amin et.al [45]	2017	Uncommon wear Index
Sarath. Kumar. K. et al.al [46]	2018	Unhealthy participants
Mulic. Aida et.al [47]	2018	Uncommon wear Index

J. Casanova-Rosado et.al [48]	2005	Uncommon wear Index
N. Ratnayak et al. [49]	2010	Type of wear not stated
P. Wetselaar et al. [50]	2016	Type of wear not stated
A. Pineda et al. [51]	2019	Wrong population
A. Millward et al. [52]	1994	Wrong population
D. Mangueiret al. al [53]	2009	Wrong population

Table 6. Summary of findings from the included studies.

S/N	Reference	Year	Country	Subject	Age group	Percentage Male	Type of Dentition	Sources
1	A.Lussi et.al. [54]	1993	Switzerland	391	26-50	N/A	P	Q&C
2	B.T. Piotrowski et al [55]	2001	USA	32	38-80	100	P	Q&C
3	Al-Majed I et.al [56]	2002	Saudi Arabia	862	12-14	100	P	Q&C
4	O.Bernhardt et.al [57]	2006	Germany	2707	20-59	46.8	P	Q&C
5	B. Liu et.al	2014	China	704	40-50	52.13	P	Q&C
6	O.Oginet al. al [6]	2002	Nigeria	126	19-80	58.7	P	C
7	E. Provatenet al. al [58]	2016	Greece	263	14	49	P	Q&C
8	O.Ogiet al.. al [59]	2003	Nigeria	106	20-80	N/A	P	Q&C

9	A. Kanet al.t.al [60]	2013	India	400	18-25	28.25	P	Q
10	Y. Kitasako et.al [61]	2015	Japan	1108	15-89	N/A	P	Q&C
11	A Pineda et.al [62]	2016	Mexico	417	14-19	61.4	P	Q&C
12	K.O Saet al.et al [63]	2018	Nigeria	1349	18-35	44	P	Q&C
13	Z.et al.et al [7]	2016	China	720	35-74	50	P	Q&C
14	D.W.Bartlett et.al [64]	2013	Europe	3187	18-35	N/A	P	Q&C
15	J.Li et.al [65]	2018	China	720	12-15	50	P	Q&C
16	I.Arnadottir et.al [66]	2010	Iceland	2251	12-15	52.6	P	C
17	M.A Harding et.al [67]	2010	Ireland	123	12	50	P	C
18	J.Casanova-Rosado et.al [48]	2005	Mexico	390	14-19	45.9	P	Q&C
19	C.D Brusius et.al [68]	2018	Brazil	801	12	N/A	P	Q&C
20	R.Huew et.al [69]	2012	Libya	791	12	50.4	P	Q&C
21	H.Aidi et.al [70]	2011	Netherlands	572	13-15	51	P	Q&C
22	L.A Louet et al. [71]	2015	Uruguay	1136	12	47.7	P	Q&C

Types of wear	**Teeth Observed**	**Wear Index**	**Number of Examiners**
33.15% Abfraction	All teeth	Lussi	2
59% Abrasion	All teeth	Automated periodontal probe	1
26% erosion	All teeth		1

		Smith and Knight (Mod)	
24.7% Abrafraction	All teeth	N/A	8
52.3% erosion and 40.9% attrition	All teeth	Smith and Knight	1
64.3% attrition	All teeth	Smith and Knight	N/A
15.9% Abrasion			
7.1% erosion			
12.7% Attrition and Abrasion			
19.4% erosion	All teeth (excluding incisal edge)	BEWE	2
62.3% Abrasion	All teeth	Smith and Knight	1
36.15% erosion	All teeth	Smith and Knight	1
26.1% erosion	All teeth	Smith and Knight (Mod)	2
31.7% erosion	All teeth	Lussi	1
60.2% erosion	All teeth	BEWE	6
83.8% erosion	All teeth	BEWE(Mod)	2
29% erosion	All teeth	BEWE	10
40.8% erosion	28 teeth	BEWE	2
66.1% erosion			
15.7% erosion	All teeth	Lussi(Mod)	1
30.7% erosion			
38% erosion	All teeth	Smith and Knight (Mod)	1
33.3% attrition	All teeth	Ordinal	4
25.4% erosion	Incisors and first molar	BEWE	2
40.8% erosion	All teeth	O’Brien	1
22.2% erosion	All teeth	Lussi (Mod)	N/A
52.9% erosion	All teeth	BEWE	2
47% erosion	All teeth	O'Brien	1

Training	Interobserver agreement Kappa	Intraobserver agreement Kappa	Effect of Gender	Effect of Diet
Yes	>0.75	N/A	NS	NS
N/A	N/A	N/A	N/A	N/A
N/A	N/A	0.89	N/A	Yes(P=0.02)
Yes	0.68-0.91	0.53-0.74	NS	N/A
Yes	N/A	0.75	N/A	Yes(P=0.024)
Yes	0.89	N/A	Yes(P=0.022)	Yes(P=0.05)
N/A	N/A	N/A	N/A	N/A
N/A	N/A	N/A	N/A	N/A
N/A	N/A	N/A	NS(P=0.221)	N/A
	0.86	0.93&0.95	N/A	Yes(p<0.05)
Yes	N/A	0.83	N/A	Yes(P=0.01)
Yes	0.855	0.855	NS(P=0.071)	Yes (OR=1.3)
Yes	>0.70	N/A	NS	Yes(P<0.001)
Yes	0.75	N/A	NS	Yes
Yes	>0.60	>0.70	NS(P=0.502)	Yes(P=0.048)
Yes	N/A	0.84	Yes(P<0.001)	
			Yes(P<0.001)	N/A
Yes	N/A	0.7	Yes(P=0.0036)	Yes
Yes	>0.85	N/A	NS(P=0.222)	N/A
Yes	0.72	>0.75	Yes(P=0.29)	Yes(P=0.46)
Yes	N/A	>0.77	Yes(P=0.004)	N/A
N/A	N/A	N/A	Yes (OR=0.51)	Yes (OR=1.04)
Yes	0.85	>0.71	Yes (OR=3.22)	N/A
Yes	N/A	0.9	N/A	Yes(P=0.043)

Q= Questionaire, C= Clinical assessment, N/A= Not Available, NS= Not Significant, P= Permanent dentition

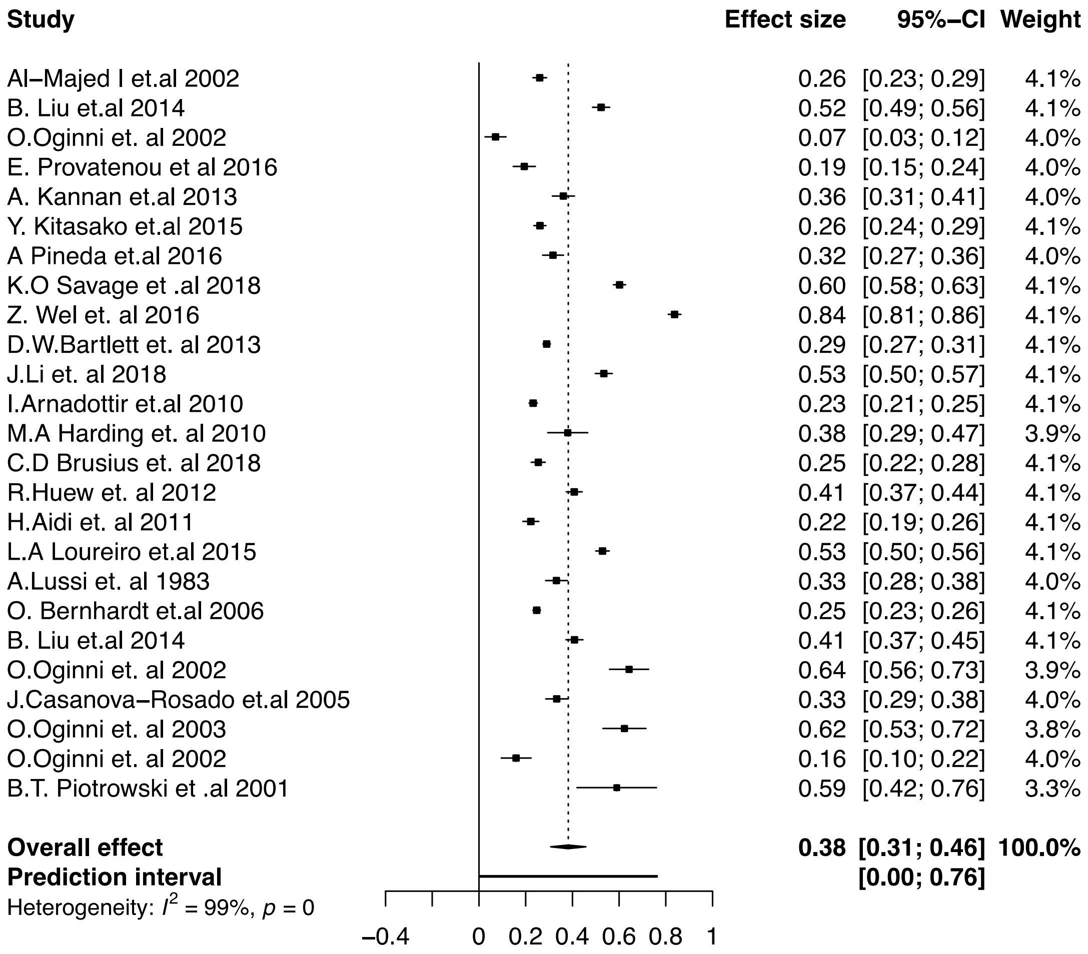
The geographical distribution of the included studies indicated that four studies were conducted in Africa, seven in Europe, five in Asia, five in the Americas, and one in the Middle East. The majority of the included articles focused on erosion as the type of tooth wear.

The forest plot (Figure 3) displayed an overall prevalence of tooth wear or effect size of 38% (95% CI: 0.31-0.46), with a prediction interval for future studies ranging from 0% to 76%. Additionally, based on J. Higgins et al. [72], the calculated I2 value indicated a substantial degree of heterogeneity with a p-value of <0.001, warranting further investigation into the sources of heterogeneity.

Subgroup analysis involved categorizing the studies into different groups, such as regions (Africa, Americas, Asia, Europe, and the Middle East) and types of tooth wear (erosion, attrition, abrasion, and abfraction). The meta-analysis of regions demonstrated a significant difference in the pooled effect sizes among the regions, with a p-value of 0.0094. Europe exhibited the lowest estimated pooled effect size at 27%, while Asia had the highest (refer to Figure 4). However, the meta-analysis of other subgroups did not reveal any significant differences in their pooled effect sizes. More details on the subgroup analysis can be found in Table 8.

The results of univariate meta-regression, presented in Table 7, indicated that only the moderator "region" contributed to the variability of the effect size, accounting for an R2 value of 7.42%. When multivariate moderators were utilized, there was no considerable difference observed in the meta-regression results.

To assess the risk of bias, a funnel plot was employed. The plot visually inspected the included studies for potential publication bias [73]. The plot exhibited a highly asymmetrical pattern, with smaller studies and smaller effect sizes missing. Only four studies fell within the 95% confidence interval of the estimated pooled effect size (refer to Figure 5). The degree of asymmetry was quantified using Egger's test [74], which revealed a substantial but statistically insignificant asymmetry in the funnel plot (intercept: 4.878, p-value: 0.323).



Study	Effect size	95%−CI	Weight
Al−Majed I et.al 2002	0.26	[0.23; 0.29]	4.1%
B. Liu et.al 2014	0.52	[0.49; 0.56]	4.1%
O.Oginni et. al 2002	0.07	[0.03; 0.12]	4.0%
E. Provatenou et al 2016	0.19	[0.15; 0.24]	4.0%
A. Kannan et.al 2013	0.36	[0.31; 0.41]	4.0%
Y. Kitasako et.al 2015	0.26	[0.24; 0.29]	4.1%
A Pineda et.al 2016	0.32	[0.27; 0.36]	4.0%
K.O Savage et .al 2018	0.60	[0.58; 0.63]	4.1%
Z. Wel et. al 2016	0.84	[0.81; 0.86]	4.1%
D.W.Bartlett et. al 2013	0.29	[0.27; 0.31]	4.1%
J.Li et. al 2018	0.53	[0.50; 0.57]	4.1%
I.Arnadottir et.al 2010	0.23	[0.21; 0.25]	4.1%
M.A Harding et. al 2010	0.38	[0.29; 0.47]	3.9%
C.D Brusius et. al 2018	0.25	[0.22; 0.28]	4.1%
R.Huew et. al 2012	0.41	[0.37; 0.44]	4.1%
H.Aidi et. al 2011	0.22	[0.19; 0.26]	4.1%
L.A Loureiro et.al 2015	0.53	[0.50; 0.56]	4.1%
A.Lussi et. al 1983	0.33	[0.28; 0.38]	4.0%
O. Bernhardt et.al 2006	0.25	[0.23; 0.26]	4.1%
B. Liu et.al 2014	0.41	[0.37; 0.45]	4.1%
O.Oginni et. al 2002	0.64	[0.56; 0.73]	3.9%
J.Casanova−Rosado et.al 2005	0.33	[0.29; 0.38]	4.0%
O.Oginni et. al 2003	0.62	[0.53; 0.72]	3.8%
O.Oginni et. al 2002	0.16	[0.10; 0.22]	4.0%
B.T. Piotrowski et .al 2001	0.59	[0.42; 0.76]	3.3%
Overall effect	**0.38**	**[0.31; 0.46]**	**100.0%**
Prediction interval		**[0.00; 0.76]**	

Heterogeneity: $I^2 = 99\%$, $p = 0$

Figure 3. Forest Plot showing the overall tooth wear prevalence from all the included studies.

Table 7. Meta-regression with different covariates

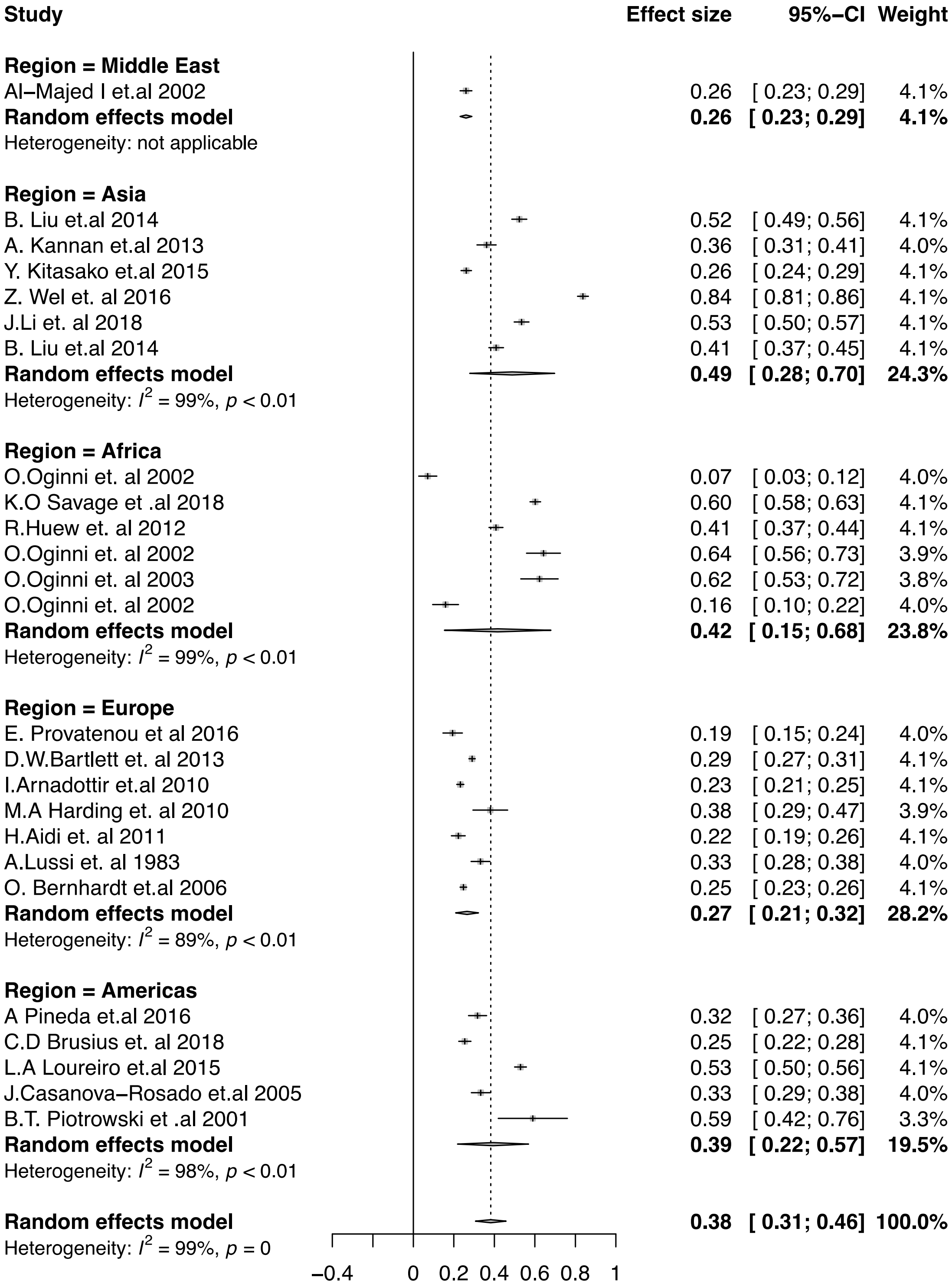
Variables	N	Meta-Regression		
		Univariate p-value	Moderators p-value	R^2 (%)
Geographical Location			0.248	7.42
Africa	4	Reference		

Americas	5	0.8690		
Europe	7	0.1538		
Asia	5	0.4824		
Middle East	1	0.4204		
Year of Publication			0.8984	0
1984-2004	5	Reference		
2005-2020	17	0.8984		
Sample Size			0.7348	0
Less than 1000	16	Reference		
More than 1000	6	0.7348		
Wear			0.7059	0
Abfraction	2	Reference		
Abrasion	3	0.3561		
Attrition	3	0.3249		
Erosion	17	0.5393		

Table 8. Subgroup analysis

Subgroup	N	Prevalence (Effect size)	p-value
Region			0.0094
Africa	4	0.42	
Americas	5	0.39	
Asia	5	0.49	
Europe	7	0.27	
Middle East	1	0.26	
Types of Wear			0.2376
Erosion	17	0.37	
Attrition	3	0.46	
Abrasion	3	0.46	
Abfraction	2	0.29	

Year of Publication			0.9333
1984-2004	5	0.39	
2005-2019	17	0.39	
Sample Size			0.7069
Less than 1000	16	0.39	
More than 1000	6	0.36	



Study	Effect size	95%-CI	Weight
Region = Middle East			
Al–Majed I et.al 2002	0.26	[0.23; 0.29]	4.1%
Random effects model	**0.26**	**[0.23; 0.29]**	**4.1%**
Heterogeneity: not applicable			
Region = Asia			
B. Liu et.al 2014	0.52	[0.49; 0.56]	4.1%
A. Kannan et.al 2013	0.36	[0.31; 0.41]	4.0%
Y. Kitasako et.al 2015	0.26	[0.24; 0.29]	4.1%
Z. Wel et. al 2016	0.84	[0.81; 0.86]	4.1%
J.Li et. al 2018	0.53	[0.50; 0.57]	4.1%
B. Liu et.al 2014	0.41	[0.37; 0.45]	4.1%
Random effects model	**0.49**	**[0.28; 0.70]**	**24.3%**
Heterogeneity: $I^2 = 99\%$, $p < 0.01$			
Region = Africa			
O.Oginni et. al 2002	0.07	[0.03; 0.12]	4.0%
K.O Savage et .al 2018	0.60	[0.58; 0.63]	4.1%
R.Huew et. al 2012	0.41	[0.37; 0.44]	4.1%
O.Oginni et. al 2002	0.64	[0.56; 0.73]	3.9%
O.Oginni et. al 2003	0.62	[0.53; 0.72]	3.8%
O.Oginni et. al 2002	0.16	[0.10; 0.22]	4.0%
Random effects model	**0.42**	**[0.15; 0.68]**	**23.8%**
Heterogeneity: $I^2 = 99\%$, $p < 0.01$			
Region = Europe			
E. Provatenou et al 2016	0.19	[0.15; 0.24]	4.0%
D.W.Bartlett et. al 2013	0.29	[0.27; 0.31]	4.1%
I.Arnadottir et.al 2010	0.23	[0.21; 0.25]	4.1%
M.A Harding et. al 2010	0.38	[0.29; 0.47]	3.9%
H.Aidi et. al 2011	0.22	[0.19; 0.26]	4.1%
A.Lussi et. al 1983	0.33	[0.28; 0.38]	4.0%
O. Bernhardt et.al 2006	0.25	[0.23; 0.26]	4.1%
Random effects model	**0.27**	**[0.21; 0.32]**	**28.2%**
Heterogeneity: $I^2 = 89\%$, $p < 0.01$			
Region = Americas			
A Pineda et.al 2016	0.32	[0.27; 0.36]	4.0%
C.D Brusius et. al 2018	0.25	[0.22; 0.28]	4.1%
L.A Loureiro et.al 2015	0.53	[0.50; 0.56]	4.1%
J.Casanova–Rosado et.al 2005	0.33	[0.29; 0.38]	4.0%
B.T. Piotrowski et .al 2001	0.59	[0.42; 0.76]	3.3%
Random effects model	**0.39**	**[0.22; 0.57]**	**19.5%**
Heterogeneity: $I^2 = 98\%$, $p < 0.01$			
Random effects model	**0.38**	**[0.31; 0.46]**	**100.0%**
Heterogeneity: $I^2 = 99\%$, $p = 0$			

Figure 4. Subgroup analysis by region

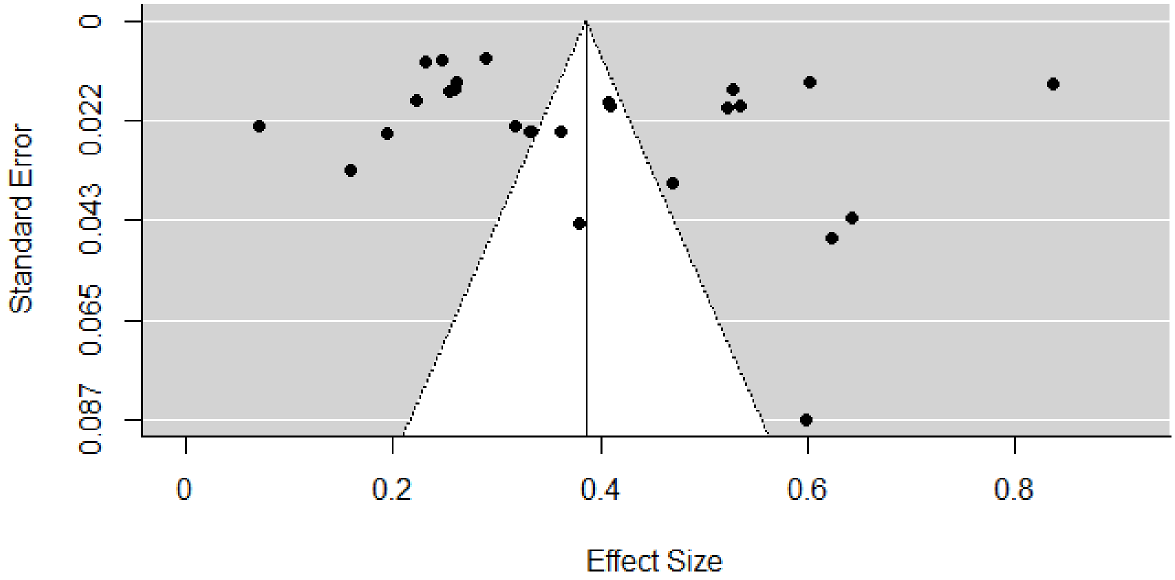


Figure 5. Funnel plot of included studies

Table 9. The Bhattacharyya Distance between subgroups within region category

Subgroups	Bhattacharyya Distance
Africa-America	36.43
Africa-Asia	36.24
Africa-Europe	36.34
Asia-Europe	36.30
America-Europe	13.47

America-Asia	13.20

Discussion

The combined studies in our systematic review yielded an estimated tooth wear prevalence rate of 38% for permanent dentition. If we exclude the two outliers from the included studies (Z. Wel et al. [7] with the highest prevalence rate of 84% and O. Oginni et al. [6] with the lowest prevalence rate of 7%), the prevalence rate could be reduced to 37%. This rate is higher than the prevalence rate reported by Salas et al. [8] in their systematic review on tooth erosion. The difference might be due to the fact that our review encompasses all types of tooth wear, not just tooth erosion, although eighteen of the included studies did report the prevalence of tooth erosion with dentin exposure.

The total number of subjects examined in the eighteen included studies was 15,530, with the smallest study including 123 subjects and the largest including 1,349 subjects. Despite the use of different wear indices in some studies, the measurement of severity was uniformly determined by dentine exposure. The age range of the participants in the studies ranged from 12 to 80 years, and we did not find any relationship between age and the prevalence of tooth wear.

Both the subgroup meta-analysis and meta-regression revealed that the region subgroup was responsible for the heterogeneity observed in our meta-analysis. To examine the relationships between subgroups within the region category, the Bhattacharyya distance (BD) was utilized. BD measures the similarities between different probability distributions, and smaller BD values indicate higher likeness in diets and lifestyles. From Table 9, it was evident that participants from Africa differed from the other regions. The Middle East was excluded from BD analysis due to the inclusion of only one study from the region.

The observed differences in BD among regions may be attributed to the fact that only three studies reported the prevalence of tooth wear erosion in Africa. Tooth wear prevalent in African populations is predominantly attrition and abrasion, which can be attributed to fibrous diets and the consumption of nuts. This finding aligns with the reports of Jeremy R et al. and A. Milosevi [75], stating that erosion is the prominent tooth wear type in the Western world due to dietary and lifestyle factors. This explains the smaller BD between the Americas and Europe.

Furthermore, approximately 77% of the included studies reported erosive wear, contributing to the global prevalence of 37%. It is hopeful that government policies can be implemented to recommend the reduction of citric/phosphoric acids in soft drinks and fruit juices, as they are major contributors to tooth erosion.

One limitation of this systematic review is that the search strategy was limited to English-language journals, which may explain why we only identified one study from the Middle East.

Conclusion

This systematic review revealed a global prevalence of tooth wear with dentin exposure at 38%. Significantly, there was heterogeneity among the included studies, with the variability primarily attributable to the geographical location of the studies.

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Chapter IV- Dental Imaging with Redundant Non-Uniformly Sampled Optical Coherence Tomography

Synopsis

This chapter presents the application of the newly developed Optical Coherence Tomography (OCT) image reconstruction method (scaled NDFT) used in this work to dentistry by using it to produce OCT images of human teeth and comparing it with the standard OCT image reconstruction method. This chapter is important because it gives detailed information about our OCT system and the image reconstruction method used for getting the OCT images. This article has been submitted for publication in the Micromachines journal.

Abstract

Optical Coherence Tomography (OCT) is a non-invasive imaging technique that provides cross-sectional images of biological microstructures. It has applications in several medical fields, e.g., ophthalmology, cardiology, and dentistry. In previous work, one of our co-authors developed a generalized image reconstruction method using redundant non-uniform OCT samples. In this paper, we used a low linearity optical source in our lab-based OCT system and the newly developed image reconstruction method to obtain OCT images of human teeth with a higher peak signal-to-noise ratio (PSNR) than the typical OCT image reconstruction method. This work shows that using high-linearity laser

sources is optional for getting high-quality OCT images. It will bring OCT closer to becoming a clinical imaging tool in dentistry.

Introduction

Optical Coherence Tomography (OCT)

This imaging technique was developed by Fujimoto et al. in 1991[1], and since then, it has been used in numerous biological imaging. To fully understand Optical Coherence Tomography (OCT), we must start with an imaging technique close to OCT and well-known to all. Ultrasound is an imaging technique that is non-invasive, non-radiating and non-ionizing. It uses the sound wave to get the image of organs or tissues by sending the sound wave to the organ through a probe and measuring the echo time delay of the backscattered sound wave; this echo time delay is then processed to get the image of the internal organs or tissues. So, instead of sound waves for detecting images in ultrasound, OCT uses light waves whose speed ($\sim 3 \times 10^8$ m/s) is way faster than the sound wave. Therefore, the rate of acquiring images is more rapid than ultrasound. Also, OCT has better image resolutions than ultrasound, and the axial image resolution of OCT is $< 20\mu m$ [2]. OCT has been used extensively in the following medical fields: ophthalmology, gastrointestinal endoscopy, dermatology, laryngology, urology, and gynaecology and recently, it has been an active field of research in dentistry.

The OCT system is divided into two broad groups: Time-Domain (TD) and Fourier-Domain (FD). FD OCT is further divided into Spectral-domain OCT and Swept-Source OCT. Fourier-domain OCT has higher sensitivity and imaging speed and therefore has wider acceptance than TD OCT[3].

The depth profiles of an object or A-scans are obtained by applying Fourier transform to the acquired data. The standard way of image reconstruction in FD OCT, especially in SS-OCT, involves the application of inverse Fourier transform to the depth or A-scan data. The inverse Fourier transform is achieved by using the Fast Fourier Transform (FFT), which computationally depends on the implementation of the Discrete Fourier Transform (DFT). The problem with this type of inversion is that DFT requires equally spaced samples in the frequency domain for good image quality. Therefore, oversampling is necessary for enough non-redundant and uniformly spaced samples needed for quality OCT image reconstruction. Redundant and non-uniformly spaced data are subsequently removed before the image reconstruction process is carried out. This extra step adds to the computation time of the whole process.

Furthermore, one of the reasons OCT systems are yet to be clinically acceptable in dentistry as imaging tools is the cost, and this is because the quality of reconstructed images depends significantly on the characteristics of the light source used in the system. High linearity and large spectral band laser sources are expensive.

Researchers have proposed several methods for acquiring uniform samples in the frequency domain to address the above issues with OCT image reconstruction [4–7], but each has its drawbacks. The latest solution to the problem was presented by one of our co-author [8], where he deployed *scaled* non-uniform discrete Fourier transform (NDFT) for the OCT image reconstruction. Using the redundant and non-uniform frequency domain samples, the method gave a higher signal-to-noise ratio (SNR) needed for excellent image reconstruction.

In this paper, we present the application of our OCT system in conjunction with the newly developed image reconstruction method [8] to dental imaging. The working principle and a detailed description of our lab-based OCT hardware system are also presented.

Working Principle of OCT

OCT is based on an optical interferometry system with a low coherence length broadband light source. The low coherence broadband light source is split into two by a beam splitter, one is sent to a reference mirror, and the other is sent to the sample. The backscattered light from the reference mirror and the sample interferes within the Michelson or Mach-Zehnder interferometer [9][10]; this constructive interference occurs when the optical path difference between the two lights is an integer multiple of the wavelength. This interference is then acquired by a photodiode and processed to get the image of the desired organs or tissues.

There are two types of scanning in OCT: Axial and Transverse. The axial scan is also known as an 'A' scan or dept scan, which measures the backscattered light from the sample against depth. Cross-sectional images created by performing different A-scans at different transverse positions are known as 'B' scans [11] (Figure 2). The earlier form of OCT known as Time Domain (TD) OCT (Figure 3) is based on a detection technique in which the reference arm moves during an 'A' scan, or dept scan.

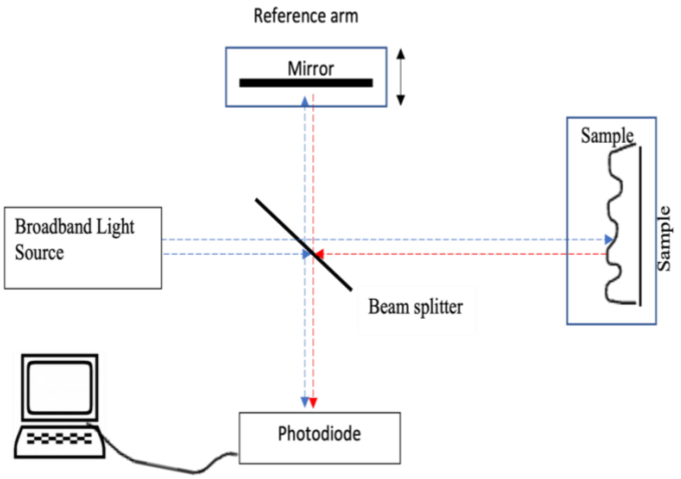


Figure 6. Time-Domain OCT Configuration (--- incidence rays, --- backscattered rays).

Although there are several functional OCT systems, they are based on either Fourier domain OCT (FD-OCT)—which could be configured as spectral-domain or swept-source—or Time Domain OCT configurations (see Figure 4 & 5).

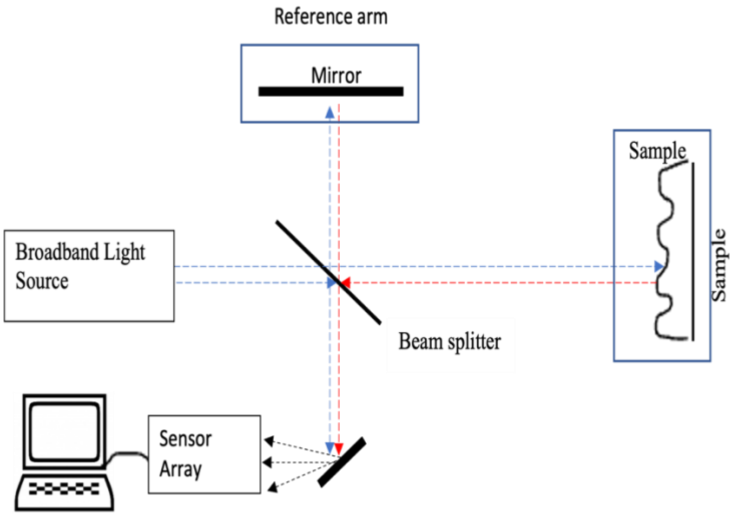


Figure 7. Spectral-Domain OCT Configuration (--- incidence rays, --- backscattered rays).

Spectral-domain FD-OCT configuration is the same as TD-OCT except that it has an additional grating for spatial Fourier transform or a spectrometer and the reference arm is stationary.

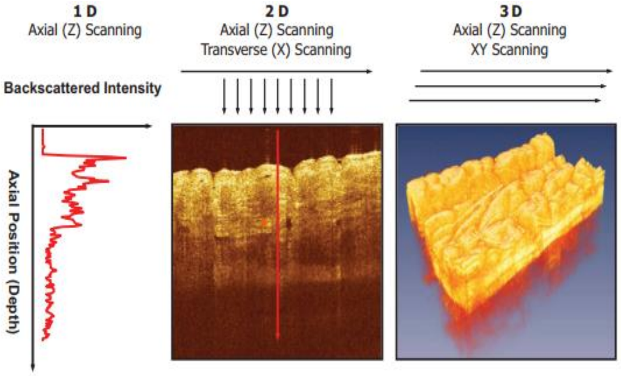


Figure 8. 1D OCT scan is known as "A" scan, 2D OCT scan known as "B" scan and 3D OCT scan known as "C" scan (reprinted from reference [11] with permission).

Signal to Noise Ratio for OCT

Signal to Noise Ratio (SNR) is used in science and engineering to refer to the ratio of the desired signal to the background noise, measured in decibels. In Michelson OCT configuration, the bulk of the optical power is lost, and only a fraction of the optical power from the light source makes it to the photodetector [12], so a higher SNR is essential for the detection of the backscattered signal from samples, especially biological tissues. SNR of an OCT is directly proportional to the optical power of the source and inversely related to the bandwidth of the photodetector; to have a high SNR at the photodetector, the bulk of the optical power is directed to the sample arm of the OCT.

The three primary sources of noise in OCT are receiver noiseσ_{re}^2, shot noiseσ_{sh}^2 and excess intensity noise σ_{ex}^2. Receiver noise results from thermal noise from the photodetector device and can be mitigated by improving the circuitry design of the photodetector module. Shot noise occurs due to the randomness in the arrival time of the photons from the monochromatic light source, while excess intensity noise is due to excess photons from the light source. For a single photodetector, the total noise and photocurrent are given by [13] as:

$$\sigma_i^2 = \sigma_{re}^2 + \sigma_{sh}^2 + \sigma_{ex}^2 \qquad (1)$$

The total photocurrent detected by the photodetector is given by

$$I_d = \rho[P_r + P_s + 2\sqrt{P_r P_s}\cos(k_o \Delta l)] \qquad (2)$$

where ρ is the instantaneous optical power incident in both OCT arms, P_r & P_s are the optical powers reflected from the reference arm and backscattered from the sample, respectively.

Therefore, based on the definition of SNR, it can be represented mathematically as:

$$\mathrm{SNR} = \frac{I_d}{\sigma_i^2} \tag{3}$$

Description of our OCT system

In SS-OCT, the characteristic of the optical source is an important parameter that determines the axial resolution and the quality of the image reconstruction. So, most researchers use optical sources with a very large spectral band (Sweep range) and high linearity to have excellent reconstructed OCT images. This adds to the overall cost of the OCT system and is one of the reasons it is yet to become a clinical imaging tool in dentistry [13]. Therefore, we designed our OCT system with less expensive and efficient parts to develop an affordable clinical imaging tool for dental applications. For example, the laser source for the optical module was a low linearized laser from the Santec laser product line.

The illustration of our OCT system is of two folds: Optical Module and Data Acquisition Module.

(a) Optical Module

The optical module consists of the Swept Source (SS)-laser, balanced detector, piezo motor, and optical fibre connectors. The power from the SS-laser was divided in two by a 2 × 2 fused fibre coupler (90:10). Ninety per cent of the power was sent to the reference arm, while the remaining ten per cent went to the sample arm (Figure 6). A polarization controller was placed at the output of the sample arm to control the polarization state of the reference arm to match that of the sample arm.

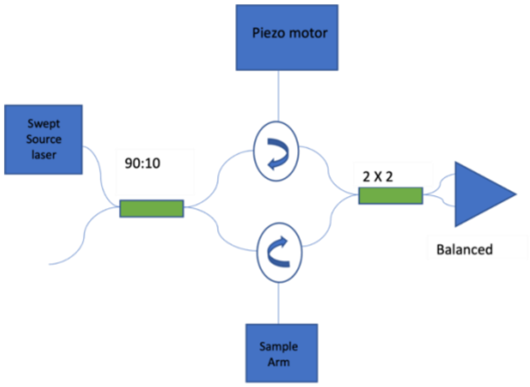


Figure 9. Swept-source OCT schematic diagram.

The beam from the laser source is collimated in the sample arm by a collimating lens before the incident on dual-axis galvo-mirrors. A telecentric objective lens brings the rays to focus onto the sample. The focused beams are back-reflected from the sample, collected by the objective lens, and then focused on the circulators. A 50/50 fused-fibre coupler combines the circulator outputs detected by a balanced heterodyne detector.

The list of optical components used in the OCT system is given in Table 5 below.

Table 10. Optical components used in the OCT system.

Optical component	Manufacturer	Part number	Task
Swept-Source (SS)	Santec	HSL-20	Swept-source laser, 1310 nm center wavelength, Wide scan range: ≥ 105 nm, Coherence length: ≥ 10 mm, Scan rate: 100 kHz
Piezo motor/controller	Newport	Conex AGP AGP-LS25-27P	Piezo motor provides a 2.5mm axial scan at 0.1 mm/s (in the air)
FC/APC fibre collimation package	Thorlabs	F280APC-C	The collimator is used to give a collimated beam (parallel waves)
XYZ $\theta_X\theta_Y$ Compact Lens Positioner	Newport	LPV-1	Five-axis lens positioner is used with the collimation package for beam alignment
5mm XY galvo mirrors	Cambridge Technology	N/A	The galvo mirrors allow the scanning on the x and y axis
Peg-joining linear stage	Newport	M-460P-XYZ-05	The galvo mirrors are attached to the linear stage for positioning
3X OCT Scan Len	Thorlabs	LSM04	The telecentric property of the focusing point on the same plane is obtained using the scan lens.
Balanced photoreceiver	Newport	1817-FC	80 MHz balanced photoreceiver

2 × 2 50/50 coupler	OZ optics	FUSED-22-1300-9/125-50/50-3A3A3A3A-1-1	The coupler splits the beam into a 1:1 ratio
2 × 2 90/10 coupler	OZ optics	FUSED-22-1300-9/125-90/10-3A3A3A3A-1-1	The coupler splits the beam into a 9:1 ratio
polarization independent fibre optic circulator	OZ optics	FOC-12N-111-9/125-SSS-1310-50-3A3A3A-1-1	The circulator is a three-port device that is used to direct the signal entering from one port to exiting the next port
Optical attenuator (optional)	OZ optics	BB-500-11-1300/1550-9/125-S-40-3A3A-3-0.5	The attenuator is used to suppress the power of the light

As stated in the previous section, the OCT system is based on interferometry, i.e., a technique in which waves are superimposed to cause interference. This phenomenon occurs when the Optical Path Length (OPL) of the reference arm is the same as the sample arm; this is done by varying the sample holding stage until the interference is detected by the balanced detector.

The sample imaging probe consists of a collimator, 2D galvo-mirrors, a telecentric lens, and a sample holding stage (Figure 7). The parameters of the sample image probe are as follows (Table 6):

Table 11. Sample Image probe parameters.

	Value (mm)
Telecentric lens length	38.5
Collimator	22.1
Scanning distance	18.9
Working distance	42.30
Parfocal distance	80.8

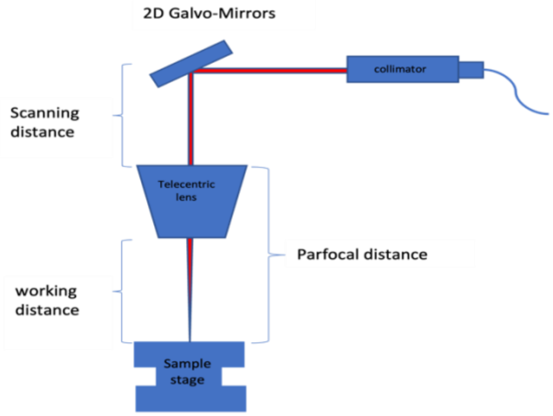


Figure 10. Schematic diagram of the sample Imaging Probe.

(i) Optical Source

The optical source used in our OCT system is HSL-20 by Santec corporation. It is a swept source laser based on Micro-Electromechanical System (MEMS), combining high-speed operation with long coherence length within a compact package. This characteristic is detailed in the measurement data graph in figure 8 below.

1. The features of the HSL-20 include:
2. 1310 nm Wavelength range
3. Wide scan range: ≥ 105 nm
4. Long coherence length: ≥ 10 mm
5. Scan rate: 100 kHz

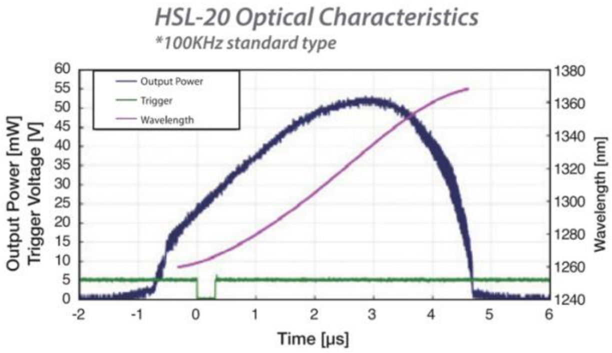


Figure 11. Measurement data for HSL-20.

(b) Data Acquisition Module

The whole Data Acquisition (DAQ) system is controlled by a LabView host application known as SS-OCT RunTimeMode (Host VI) embedded in the PXIe-8102 (Figure 9). The function of this application is to synchronize the other boards and also to receive data from the data board.

The control and the data boards communicate through the trigger lines. The control board use the PXI-Trig0 to instruct the data board to start acquiring data, while the data board uses the PXI-Trig1 line to inform the control board when done with the data acquisition.

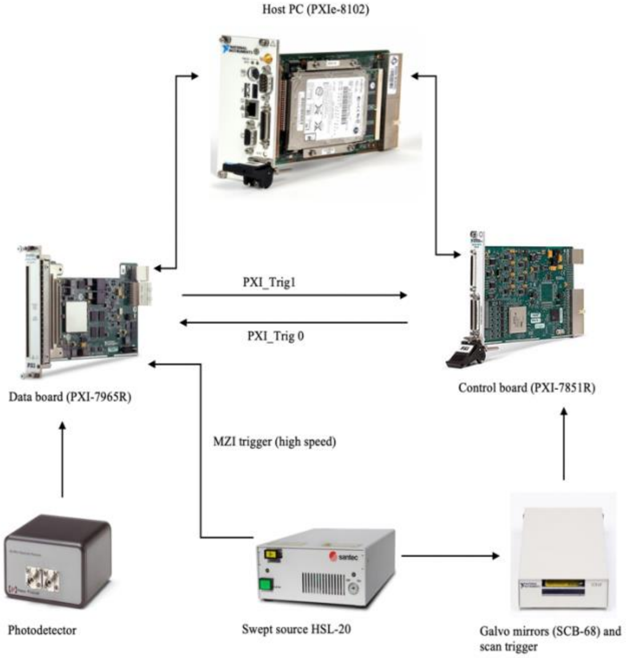


Figure 12. SS-OCT system Architecture.

(i) Control board FPGA code

The control board field-programmable gate array (FPGA) code is characterized by a loop which oversees reading the trigger signal coming from the data board and then triggers the data acquisition process once a new sweep is detected (Figure 10). Furthermore, it is also responsible for driving the galvo mirrors to the next positions when the data board is done with the acquisition.

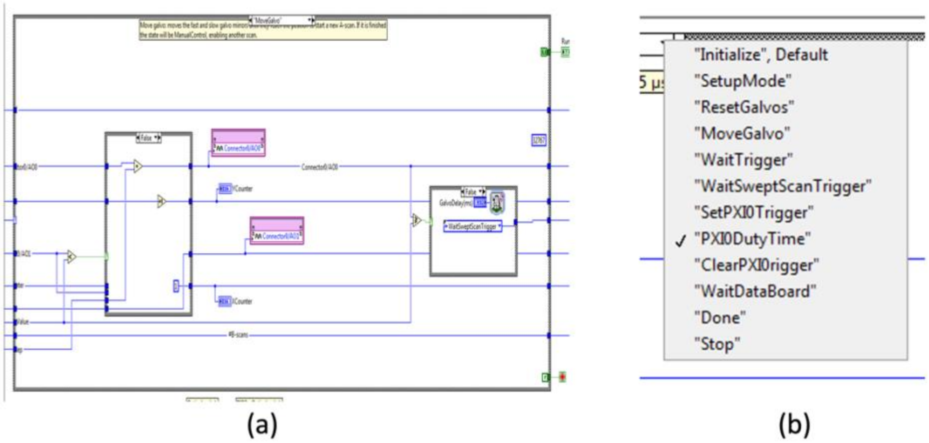

Move galvo: moves the fast and slow galvo mirrors [illegible] start a new A-scan. If it is finished the state will be ManualControl, enabling another scan.

Figure 13. Control board FPGA code diagram.

The loop assumes several states based on different situations.

1. Initialize: controls the inputs and outputs of the control board by designating PXI_Trig1 as input and PXI_Trig0 as output.
2. ResetGalvos: moves the galvo to the beginning position for new data acquisition.
3. MoveGalvos: controls the two galvo mirrors (fast and slow) to the position for the new A-scan.
4. WaitTrigger: this works similarly as the 'Run' button.

5. WaitSweptScanTrigger: receives a trigger from the swept source, initiating the beginning of a new sweep.
6. SetPXI0Trigger: this instructs the data board to start the acquisition once the control board receives the trigger from the swept source laser.
7. WaitTriggerDutyTime: this sets the time in μs that the trigger line will remain high before going to the low level.
8. ClearTrigger: set the trigger line to a low level.
9. WaitDataBoard: this state waits for the PXI_Trigg1 to go low before driving the galvos again.
10. Done: the control board goes to this state when the set number of B scans is reached.
11. Stop: the control board goes to this state when an error occurs or when the host application is closed.

(ii) Data board FPGA code

The data board FPGA code consists of five interconnected loops whose primary functions are acquiring, storing, processing, and sending the data to the host computer.

The five loops from top to bottom are:

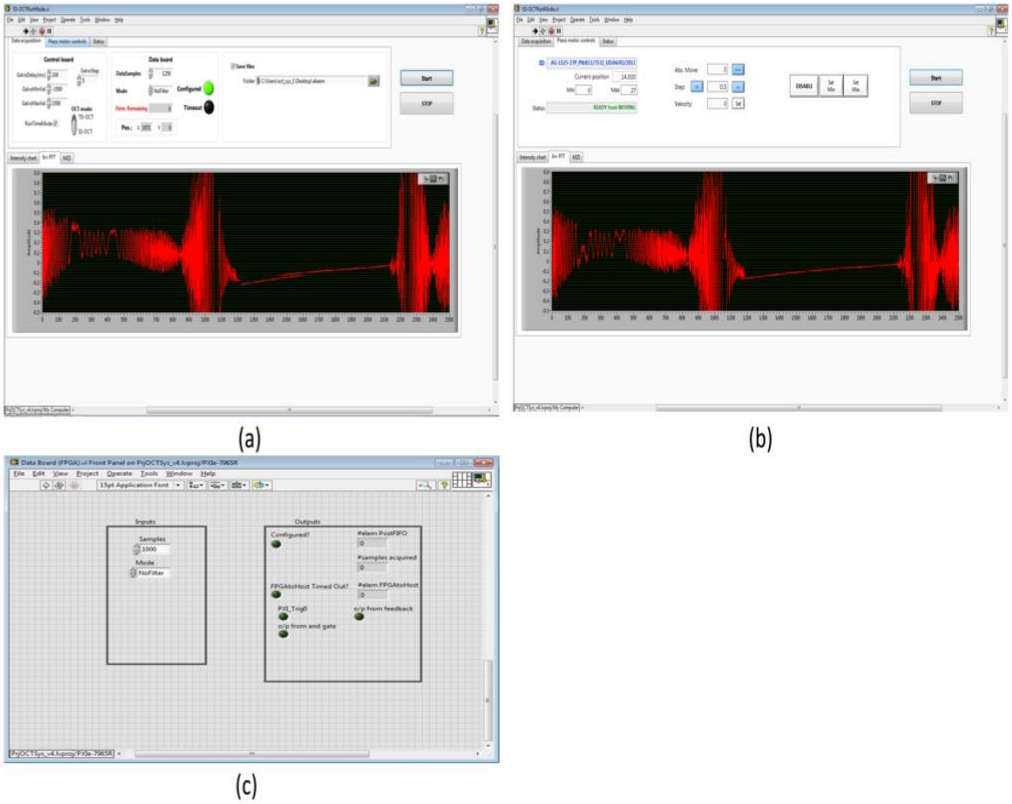
1. Calibration Loop:
2. Acquisition Loop

3. InvFFTProcessing Loop
4. PostBuffer Loop
5. FPGA to Host Loop

(iii) Host application known as SS-OCT RunTimeMode (Host VI)

This is the main program that controls everything within the OCT system. It is responsible for the Mach-Zehnder Interferometer (MZI) sampling, reading of data from the data board and in charge of driving the piezo motor.

In the front panel, there are several control buttons; some are responsible for setting the galvo range and delay between its steps, while some are for initializing and stopping data acquisitions (Figure 11a). The main program's section is dedicated to independently controlling the piezo motor. It can display the current position of the reference mirror, and the user can set the absolute movement in some defined steps (Figure 12b). We present the final setup of our lab-based Oct system in figure 13.



Samples: 1000
Mode: NoFilter
#elem PostFIFO: 0
#samples acquired: 0
#elem FPGAtoHost: 0

Figure 14. (a) Data board FPGA front panel. (b) LabVIEW front panel of the Host application (c) LabView front panel of the piezo motor control.

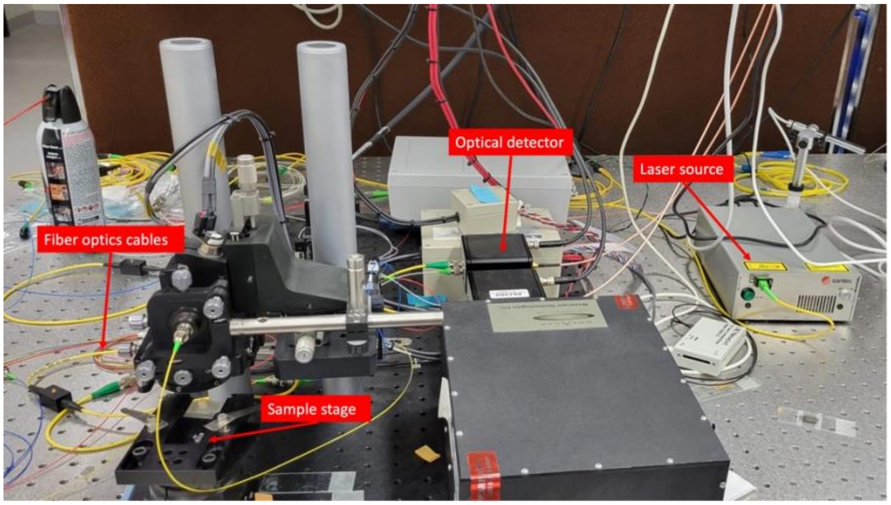


Figure 15. OCT system setup.

Results and Discussions

After the discovery of OCT in 1991 by Fujimoto et al., it took nearly seven years before the technology was applied to dentistry. The utilization of OCT in dentistry stemmed from the limitations of X-rays in accurately diagnosing carious lesions and distinguishing between active and inactive dental diseases. Additionally, X-rays provide limited information about soft tissues such as the gingiva and oral mucosa, and they are unable to detect periodontal diseases until significant bone loss occurs [14].

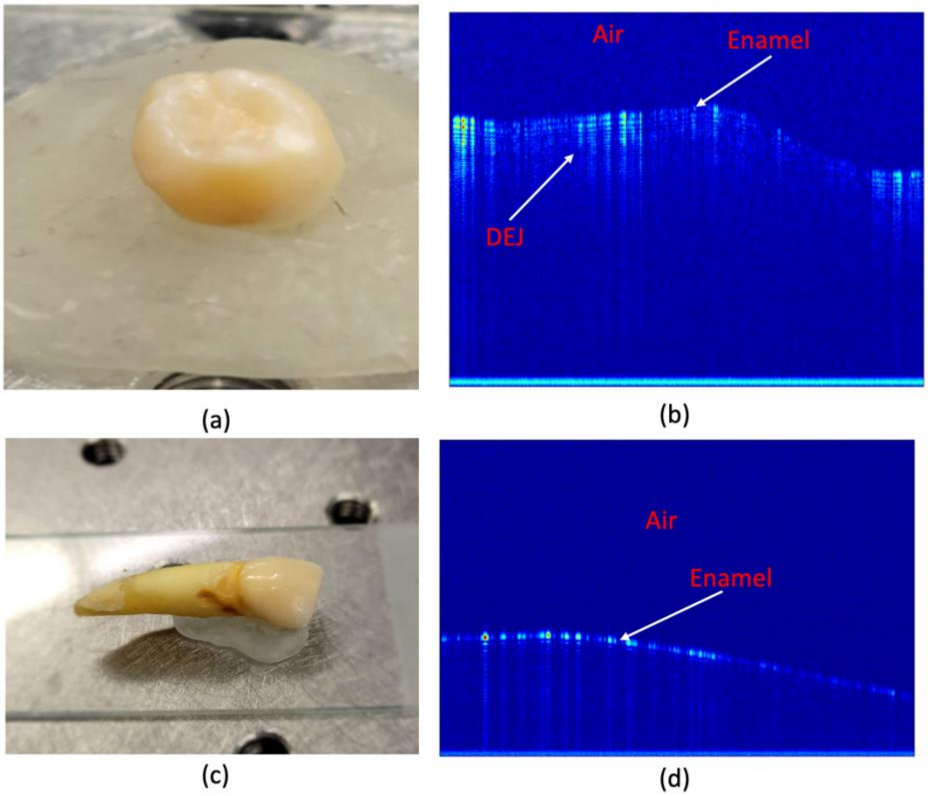
Researchers have employed OCT in various areas of dentistry, both in vitro and in vivo, including tooth cracks and wear, periodontal disease, dental restoration, and dental caries. In 1998, Colson et al. reported the first in vitro OCT image [15]. They utilized TD-OCT with a central wavelength of 1310 nm to image the teeth of a young pig and conducted comparative studies with a photomicrograph of less than 17 μm resolution of the same teeth. The first in vivo application was carried out by Otis et al. in 2000 [9], where they used OCT to image both hard and soft dental tissues at a relatively high resolution.

In SS-OCT, depth profiles of an object are obtained by Fourier transforming the acquired data, known as an A-scan. A series of A-scans are combined to produce a tomographic or sectional image (B-scan). Volumetric images of the object can be obtained by combining multiple B-scans.

OCT systems require highly linear laser sources. However, most swept source lasers exhibit deviations in laser frequencies from a linear extrapolation over the scanning period. These deviations can be attributed to mechanical limitations in the tuning elements of the lasers. Consequently, recalibration of the acquired data using an external frequency monitor and a rescaling algorithm may be necessary to achieve uniformly spaced sample data [16][17]. This additional step increases computation time and can hinder real-time imaging with OCT.

To ensure high-quality image reconstruction, the acquired data must be uniformly spaced during sampling and should not contain redundant data. Therefore, the options are either using costly high linearity laser sources or developing an image reconstruction method capable of utilizing non-uniformly spaced and redundant sample data.

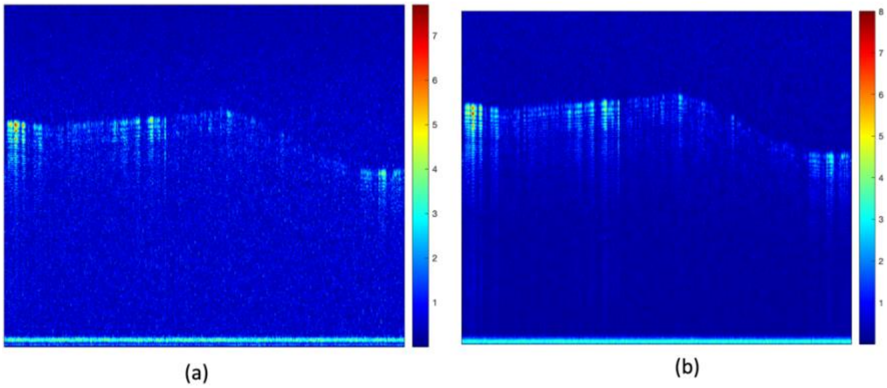
One of our co-authors has developed an image reconstruction method that significantly enhances the quality of OCT images while utilizing redundant and non-uniformly spaced OCT samples. The quality improvement was quantified by comparing the peak signal-to-noise ratio (PSNR) of different images with varying oversampling ratios [8].



(a) (b) (c) (d)

Figure 16. (a) Human molar. (b) OCT B-scan of human molar. (c) Human incisor. (d) OCT B-scan of human incisor.

So, we used our OCT system with the recently developed image reconstruction method to produce the substructural images of the human molar and incisor teeth. The molar cusp and the curvature of the incisor were visible from the OCT reconstructed B-scan image (Figure 14 b & d).



(a) (b)

Figure 17. Reconstructed OCT B-scan image of the human molar using: (a) standard FFT (b) our scaled NDFT.

In addition, we conducted a comparison of the OCT image reconstruction quality between our scaled NDFT method and the standard FFT method (Fig. 17). To assess the image quality, we generated a reference image using 10,000 sample points and then applied an averaging technique to reduce noise. Subsequently, we calculated the Peak signal-to-noise ratio (PSNR) between the reconstructed images obtained from the two methods and the reference image. The PSNR value between the two images was measured at 25.79 dB (Table 12), indicating that our scaled NDFT approach produced clearer images with enhanced visualization of the substructure of human teeth.

Table 12. PSNR between the reference image and images reconstructed from standard FFT and scaled NDFT.

Image Reconstruction Method	**PSNR (dB)**
Standard FFT	17.24
Scaled NDFT	25.79

Conclusions

We utilized our laboratory OCT system along with the newly developed image reconstruction method, scaled NDFT, to capture OCT images of human teeth using non-uniformly spaced frequency domain samples. As a result, we obtained reconstructed images with a significantly improved signal-to-noise ratio (PSNR).

OCT is a highly valuable imaging system in dentistry due to its non-invasive and non-contact nature. It is rapidly gaining recognition as a primary diagnostic tool in the field. Based on our findings, we have a strong belief that OCT will soon become a widely adopted imaging tool in dental practices.

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Chapter V- Sample preparation and wear emulation procedure

Synopsis

This chapter presents the steps in preparing samples used in this work and the description of the custom wear machine deplored for the wear emulation on the samples.

Introduction

Tooth wear is an inevitable process, and excessive wear can impair the tooth's primary function, which is the mastication of food, and may also lead to other oral disorders [1]. Dental materials are commonly used to restore the integrity of damaged teeth. These materials are broadly classified into metals and alloys, ceramics, polymers, and composites [2]. Each category has its own advantages and disadvantages. For instance, composite-based materials offer good aesthetics and can be applied using direct techniques, which saves time and money, but they may not be as durable as amalgam [3]. Therefore, dentists have a responsibility to carefully consider various factors before selecting a suitable material for dental restorations.

Methodology

The restorative materials chosen for this study are Amalgam and Composites, including both Low and High viscosities. Amalgam is an alloy of mercury and other metals that has been used for dental restorations for over one hundred and fifty years. One of the advantages of amalgam is its high wear resistance, which contributes to its long-term durability, particularly for posterior restorations. However, some patients reject amalgam due to safety concerns and aesthetic reasons. According to systematic longitudinal reviews, the Median Survival Time (MST) of amalgam in private dental practices ranges from 7.1 to 44.7 years [4].

On the other hand, composite restorative materials are synthetic filling materials composed of composite resin and chemically bonded fillers. They are designed to match the natural color of the tooth, making them a more aesthetically appealing choice for patients. However, composite restorations are more costly than amalgam because their placement requires more time compared to amalgam restorations.

(a) Sample preparation

In this study, we prepared a total of ninety restorative samples by mounting the restorative materials on acrylic polishing blocks. The acrylic blocks were created by thoroughly mixing a liquid monomer and powder polymer in the correct proportions and allowing them to undergo self-curing polymerization for thirty minutes until they hardened. The samples had an average diameter of 10 mm (Figure 18). To achieve a flat surface, we used #120, #200, #600, #1200, and #1500 grit SIC paper in sequential order on an automated grinding and polishing machine, while ensuring a continuous flow of deionized water.

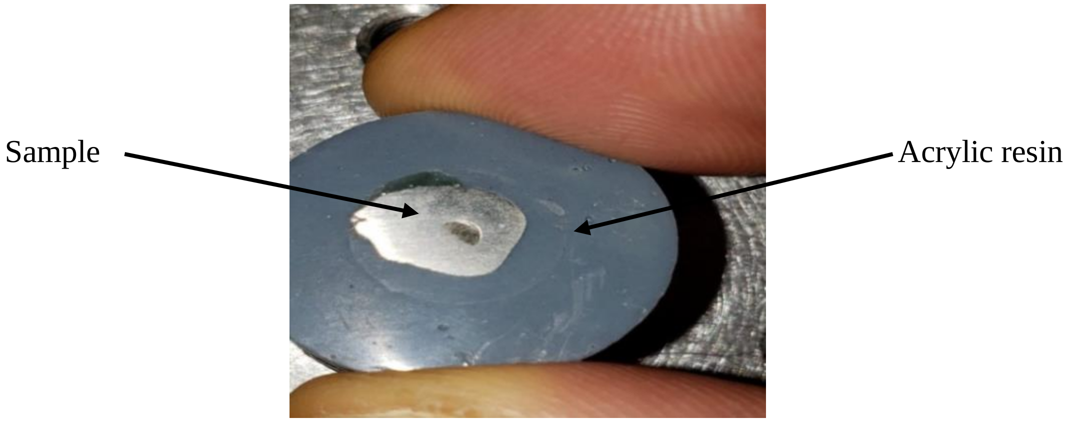
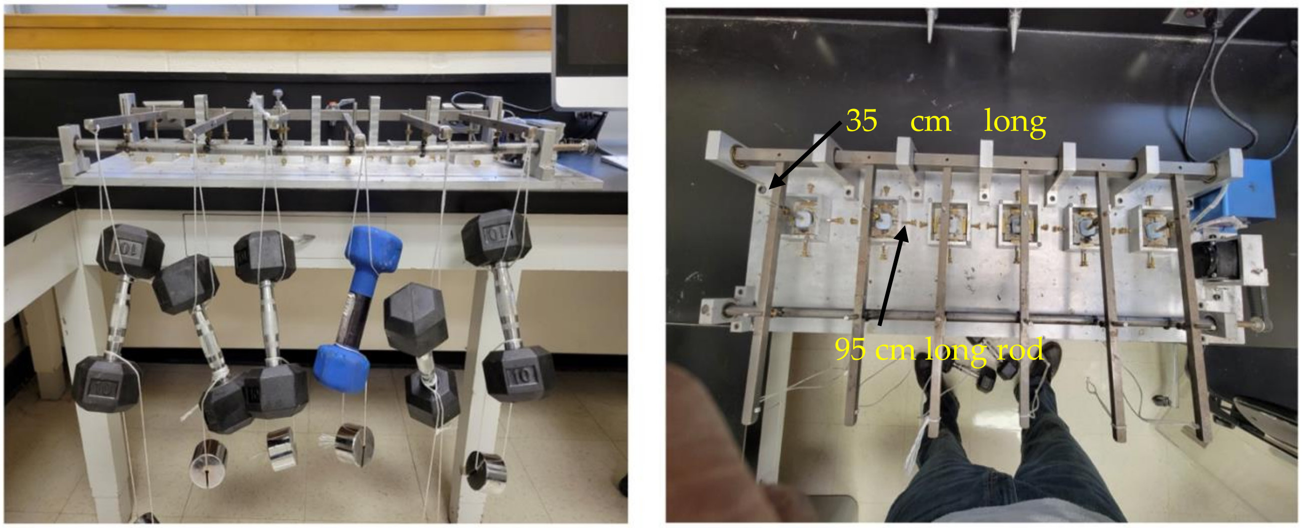


Figure 18. Amalgam sample mounted on an acrylic block.

(b) Custom-wear Machine

Due to the travel restrictions imposed by governments during the Covid-19 pandemic, we developed a customized wear machine to simulate wear on the three different restorative materials utilized in this study. The wear machine was a modified version of the two-body contact wear model. We subjected a total of ninety samples, with thirty samples each from amalgam, low-viscosity composite (LV_composite), and high-viscosity composite (HV_composite), to a 24-hour wear simulation.



(a)

(b)

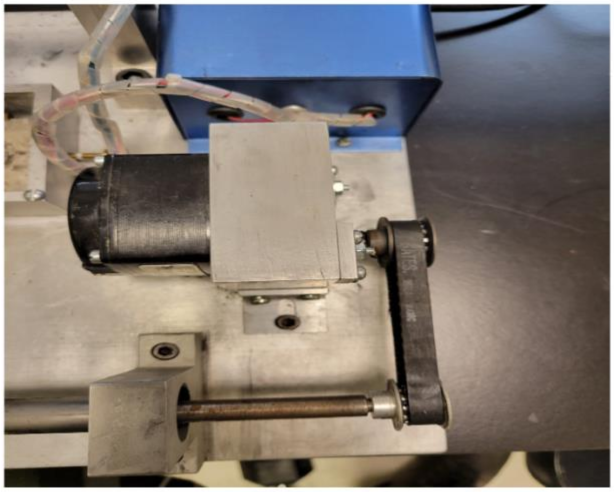
Figure 19. (a) The custom wear machine with the 5 kg weights. (b) The top view of the custom wear machine.

The wear machine was constructed using steel as the primary material. The base of the machine measured 100 cm in length, 50 cm in width, and 10 cm in thickness. It featured six 35 cm long bars, each capable of independent movement. To simulate the biting force exerted during tooth wear, 5 kg weights were attached to the end of each long bar (see Fig. 19a & b).

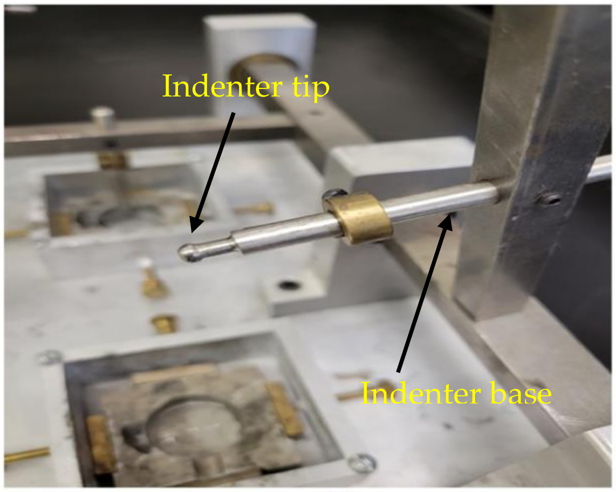
Additionally, the wear machine included a 95 cm long rod with a diameter of 16 mm. This rod was equipped with six screws strategically placed and adjusted to allow a vertical movement of 10 mm in a single long bar at a time (see Fig. 20a & b).

(a)

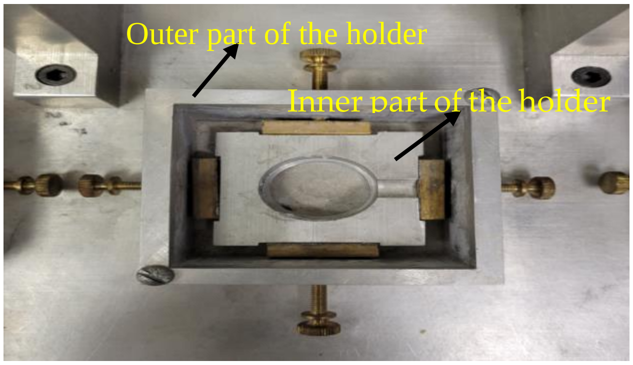
(b)



(c)


Indenter tip
Indenter base

(d)


Outer part of the holder
Inner part of the holder

(e)

Figure 20. (a) The 90 cm long rod showing some screws. (b) The rod and the bar in contact. (c) AC motor connected to the 90 cm long rod by a rubber belt. (d) The custom wear machine indenter. (e) Sample holder.

An essential component of the customized wear machine was an AC motor, which operated at a speed of 30 revolutions per minute. The motor was connected to one end of the rod using a rubber belt (refer to Figure 20c). The wear machine indenter was constructed from steel and featured a base with a diameter of 6.3 mm and a spherical tip with a diameter of 4.5 mm. With the motor in operation, the indenters made approximately 43,200 contacts per sample during the 24-hour testing period.

To ensure the stability of the samples, holders and screws were utilized. The sample holders consisted of two parts: the outer and the inner. The outer part was a hollow cube measuring 62.5 mm in length and 10 mm in thickness. It was securely fastened to the base of the wear machine using two screws. The inner part was a square washer with dimensions of 47 mm and a diameter of 21 mm (see Figure 20e).

(c) Surface Profiler

The profilometer employed in this study was the Tencor Alpha-step 500 (refer to Figure 21). It is a stylus-based profiler equipped with a 5 µm radius tip and a stylus load of 8.1 mg. This instrument measures the profile of the sample by delicately running the stylus along the surface, with the vertical deflection indicating changes in step height. The profiler offers a measurement range of step heights from 500 Angstroms to 300 µm, and its scan length spans from 100 Angstroms to 0.3 mm [5].

This equipment was chosen as the gold standard in our research due to its exceptional sensitivity and accuracy in capturing depth profiles.

Figure 21. Tencor Alpha-step 500 Profilometer

Conclusion

We provided an overview of the restorative material samples utilized in this study and outlined the preparation process. Furthermore, we presented a comprehensive description of the custom wear emulating machine and the surface profiler.

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Chapter VI- Quantification and comparison of wear in dental restorative materials using Optical Coherence Tomography

Synopsis

This chapter focuses on the capacity of Optical Coherence Tomography (OCT) to quantify wear. It is divided into two sections. The first part discusses the calibration of OCT for wear measurements and compares the results with the standard method (Surface Profiler). The agreement between the two methods is statistically analyzed. The second part compares the wear rates in three different restorative materials measured solely by OCT.

Abstract

Objective: The objective of this study was to quantify and compare the wear rates in amalgam, composite low-viscosity, and high-viscosity using Optical Coherence Tomography (OCT).

Materials and Methods: This work was divided into two parts. In the first part, thirty samples prepared from amalgam underwent wear emulation using a custom-made wear machine for 24 hours. The wear depths were then evaluated using OCT and the standard method, Surface Profiler (SP). The agreement between the two methods was assessed using intra-class correlation coefficients (ICC), Bland-Altman plots, and the difference between means. In the second part, two additional dental restorative materials (composite low-viscosity and composite high-viscosity) were prepared following the same procedure as amalgam, and their wear rates were measured using OCT only. The results were analyzed using ANOVA and Tukey's post hoc test.

Results: The findings from the first part of our study revealed that a pixel from wear depth measurements obtained by OCT corresponded to 5.24 ± 0.22 μm. The depth measurements obtained from both methods (SP & OCT) showed excellent agreement (ICC = 0.99). However, Bland-Altman plots indicated a significant systematic difference of 6.04 μm between the two measurement methods. Additionally, the difference between the means of the two measurements was not statistically significant (p-value = 0.053). In the second part, ANOVA analysis of wear depth measurements for the three different restorative materials demonstrated statistically significant differences in wear depth rates among them (p-value < 0.001). Tukey's post hoc test revealed that the mean wear rate in amalgam was significantly different from the other materials.

Conclusions: OCT can be employed clinically to quantify depth profiles in dental restorative materials without the need for additional length (depth) measuring applications.

Introduction

Tooth enamel, the hardest substance in the body, is composed of approximately ninety-six percent mineral and has an average Vickers hardness of 283 and an average elastic modulus of 1.3 GPa. These mechanical properties contribute to its excellent wear resistance. However, despite its unique characteristics, tooth wear is inevitable due to the harsh oral environment. In a fair oral environment, the wear rate of a healthy tooth ranges between 10-40 μm per year. However, in environments exposed to temperature shock, acid attacks, poor dental hygiene, and unhealthy eating habits, the wear rate can be significantly higher.

Tooth wear is an irreversible gradual loss of dental hard tissue and can be classified into two major categories: mechanical wear (attrition, abrasion, and abfraction) and chemical wear (erosion). Studying and quantifying the progression of tooth wear is crucial because macro-wear, which is visible to the naked eye, can significantly impact individuals' eating habits and overall well-being. Our recent publication on the prevalence of tooth wear in permanent teeth revealed that 38% of the data from globally published articles in the past four decades reported severe tooth wear.

In most cases, damaged enamel is restored using dental restorative materials such as amalgam, composite, or ceramics. Unfortunately, the wear rates of these materials far exceed those of natural teeth.

Optical coherence tomography (OCT) is an imaging technique based on optical interferometry with a low coherence length broadband source. It splits the low coherence broadband light into two paths—one directed towards a reference mirror and the other towards the sample. The backscattered light from both the reference mirror and the sample interferes within a Michelson or Mach-Zehnder interferometer. This interference occurs when the optical path difference between the two lights is an integer multiple of the wavelength. The resulting interference pattern is acquired by a photodiode and processed to generate images of desired organs or tissues. OCT offers better image resolution than ultrasound, with an axial resolution of <20 μm. It has been extensively used in various medical fields, including ophthalmology, gastrointestinal endoscopy, dermatology, laryngology, urology, gynecology, and more recently, in dental research.

OCT was developed by Fujimoto et al. in 1991 and has emerged as the most clinically viable alternative to X-rays in dentistry. However, to our knowledge, no study has yet tested the use of OCT to quantify dental wear without relying on secondary length (depth) measuring applications like ImageJ or screen rulers. We believe that such apps can introduce errors when quantifying wear.

Current clinical wear detection methods involve complex techniques and multiple steps, such as oral cavity impressions and cast reproduction, followed by microscopic analyses. These techniques are time-consuming, expensive, and not 100% accurate.

Therefore, the objective of this study is to evaluate the capability and accuracy of OCT in measuring wear depth in dental restorative materials compared to a micro-Surface Profiler (SP), without the need for secondary measuring software. The null hypotheses are as follows: 1. There is no difference between OCT and SP results. 2. The dental restorative materials exhibit the same wear rates.

Methods

(a) Study design

Ninety samples were prepared from three different restorative materials: Amalgam, Low-viscosity Composite resin, and High-viscosity Composite resin (Tables 13 & 14). These samples were subjected to wear emulation using a custom-made wear simulator for 24 hours. The experiment was divided into two parts.

In the first part, the objective was to assess the capability of OCT in quantifying wear depths in the restorative materials. For this purpose, the wear depths of the amalgam samples were evaluated using both OCT and a micro-Surface Profiler (SP). The OCT was calibrated using the wear depth results obtained from the SP, and its ability to measure wear depth was compared to the SP method.

In the second part of the experiment, the aim was to compare the wear rates in the three different restorative materials using OCT alone.

Table 13. Properties of the Amalgam material according to the manufacturer's datasheet

Code	**Amalgam**
Commercial name	Permite capsules[+, ‡] (non-gamma 2 admix spherical alloy)
Composition by weight	Silver (56%), Tin (27.9%), Copper (15.4%), Indium (0.5%), Zinc (0.2%) and Mercury (47.9%)
Fabricant	Lathe cut
Reorder/Lot code	4022303/1605055

+ Regular set, 600 mg alloy, and 552 mg mercury., ‡ SDI Limited, Bayswater, Victoria, Australia.

Table 14. Properties of the Composite resin materials used according to the manufacturer's datasheet

Code	**LV_composite**	**HV_composite**
Commercial name	TPH Spectra Universal Composite Restorative**(Low Viscosity)	TPH Spectra Universal Composite

		Restorative**(High Viscosity)
Matrix/Fillers	Bis-GMA resin; TEGDMA; Polymerizable Dimethacrylate Resin; CQ photoinitiator; Ethyl-4(dimethylamino)benzoate photo accelerator; BHT; UV stabilizer; Silanated bariumalumino-borosilicate glass; Silanated barium-boron-fluoro-alumino-silicate glass; Silicon dioxide; Fluorescent agent; Synthetic Inorganic Iron oxide pigments, and Titanium dioxide.	Bis-GMA resin; TEGDMA; Polymerizable Dimethacrylate Resin; CQ photoinitiator; Ethyl-4(dimethylamino)benzoate photo accelerator; BHT; UV stabilizer; Silanated bariumalumino-borosilicate glass; Silanated barium-boron-fluoro-alumino-silicate glass; Silicon dioxide; Fluorescent agent; Synthetic Inorganic Iron oxide pigments, and Titanium dioxide.
Filler$^{+,\S}$	75.5%, ~ 15 μm	77.2%, ~ 15 μm
LOT/colour	170328/A2	171200711/A2

+Weight%, § Size of fillers

**DENTSPLY International

CQ, Camphor quinone; BHT, Butylated hydroxytoluene; Bis-GMA, bisphenyl A glycidyl methacrylate; TEGMA, tri-ethylene-glycol-dimethacrylate

(b) Preparation of the restorative materials samples

Ninety restorative samples were prepared by mounting the restorative materials onto acrylic polishing blocks. The acrylic blocks were created by thoroughly mixing a liquid monomer and powder polymer in the correct proportions. The mixture was then allowed to undergo self-curing polymerization for thirty minutes until it reached a rigid state. The average diameter of the samples was 10 mm. To achieve a smooth surface, the samples were flattened using #120, #200, #600, #1200, and #1500 grit SIC paper in successive steps on an automated grinding and polishing machine, with deionized water running throughout the process.

(c) Emulation of wear on samples

The custom-made wear machine utilized in this study is a modified version of the two-body contact wear model. It consisted of an AC motor operating at a speed of 30 revolutions per minute. The motor drove a metallic rod, to which an offset CAM was affixed. Directly above the rod, six identical steel indenters were attached to a metal bar. These metal bars had the capability of independent vertical movements. The indenters were specifically designed to have a vertical displacement of 10 mm and make contact with the surface of the stationary samples during each revolution. Throughout the entirety of the experiment, a load of 5 kg was applied to each bar that carried the steel indenters.

(d) Evaluation of wear depth with Surface Profiler

An Alpha-step 500 profilometer (Tencor) scanner with a 5 μm radius tip and stylus load of 8.1 mg was utilized as the standard method in this study. The stylus was placed onto the surface of the samples, which moved at a constant speed of 3 μm/sec to obtain variations in height (depth profile). To achieve more precise stage movement, a linear piezo stage (Newport Conex-AG) was attached to the Alpha-step stage. The scanning process was conducted at the beginning of the indentation with a step size of 200 μm using the zoom function on the surface profiler (Fig. 22). The maximum scanning range for this method is 2 mm. Since the scanning pin would not reach the reference part of the sample (right side of the indentation) during stepwise scanning, it was necessary to shift the sample to the left using the profiler stage (X-axis). However, this resulted in distortion in the reconstruction image of the surface profiler. The maximum depth from each scan was recorded, and the average depth was calculated from a total of 10 scans for each sample.

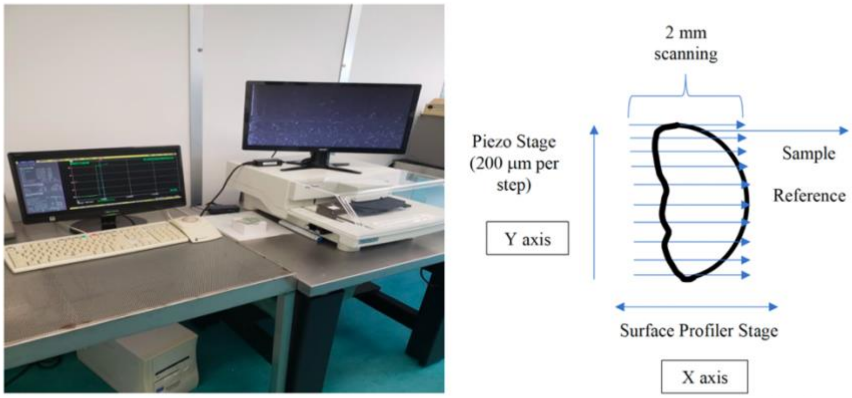


Figure 22. Surface profiler and the top view schematic diagram of the Surface profiler stage set-up.

(e) Evaluation of wear depth with OCT

The cross-sectional images (b-scan) of the samples were captured using a Swept Source OCT with a center wavelength of 1310 ± 30 nm and a scanning rate of 100 ± 0.1 kHz. The coherence length of the OCT system was 20.4 mm. Although the maximum lateral scan capability of the device was 14 mm x 14 mm, it was adjusted to 5 mm x 5 mm using the system's galvo mirrors.

To replicate the scanning procedure performed on the surface profiler (SP), a piezo stage (Newport) and an Opti-TekScope (digital USB microscope camera) with a zoom function were also attached to the OCT stage. Apart from the operational differences between the two methods, there was a distinction in the stage setup, as the scanning range for OCT was greater than that of the SP.

The initial b-scan was captured at the beginning of the indentation in the X-axis direction, and subsequent b-scans were obtained by moving the piezo stage in the Y-direction with a step size of 200 µm (Fig. 23). A total of ten b-scans were obtained for each sample.

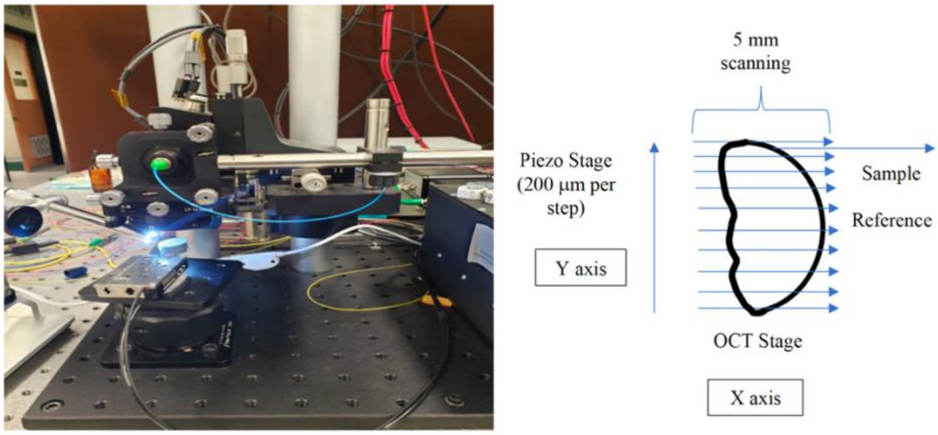


Figure 23. OCT Setup and the top view schematic diagram of the OCT stage set-up.

(f) Image registration of the reconstructed 3D images for the two depth measuring methods

To accurately evaluate the wear depth using OCT, the first step was to calibrate it. It was crucial to ensure that the indentation spot measured using the surface profiler (SP) was the exact spot being evaluated with OCT. To achieve this, the image registration technique was employed to align and register the two reconstructed images. The OCT 3D image served as the fixed image, while the surface profiler 3D image served as the moving image (Fig. 24). An affine linear transform was applied to the moving image, and the quality of the registration was assessed using Mattes Mutual Information.

Once it was established that the two reconstructed images corresponded to the same spot on the sample, the number of pixels representing the wear (airgap) was calculated from the OCT b-scans, as depicted in Fig. 25a. The OCT calibration was performed by plotting the maximum depth values obtained from each scan using the SP method against the corresponding pixel values obtained from the OCT method. The regression line was forced to pass through the origin, as it was expected that when the SP recorded an approximate zero-depth, the OCT pixel value would also be zero. The slope of the regression line was determined to be 5.24 ± 0.22 microns/pixel (Fig. 25b).

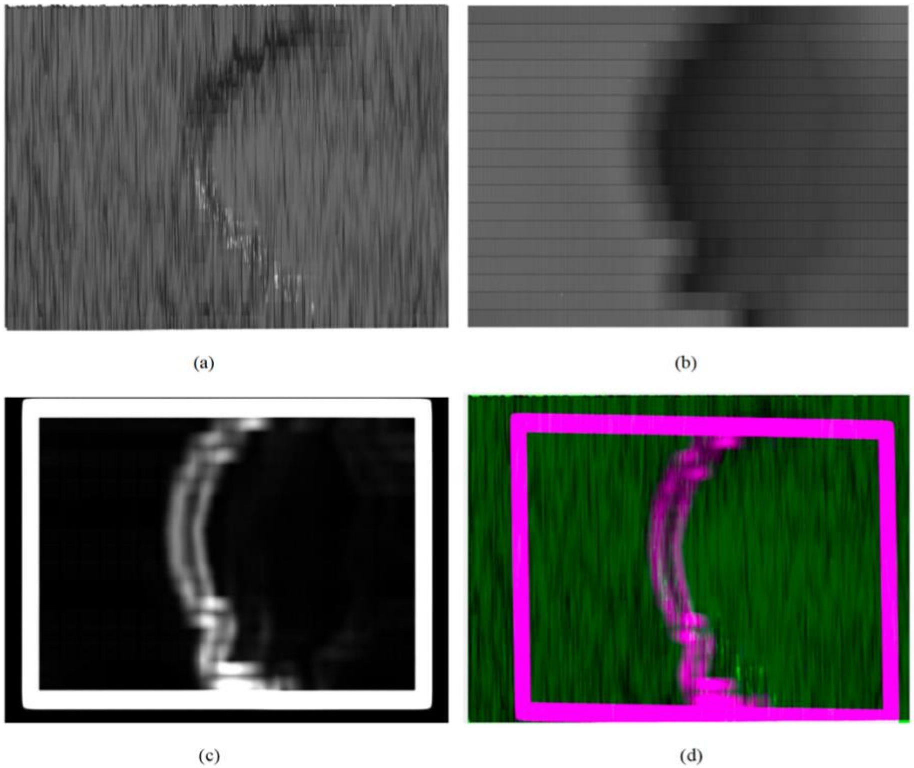
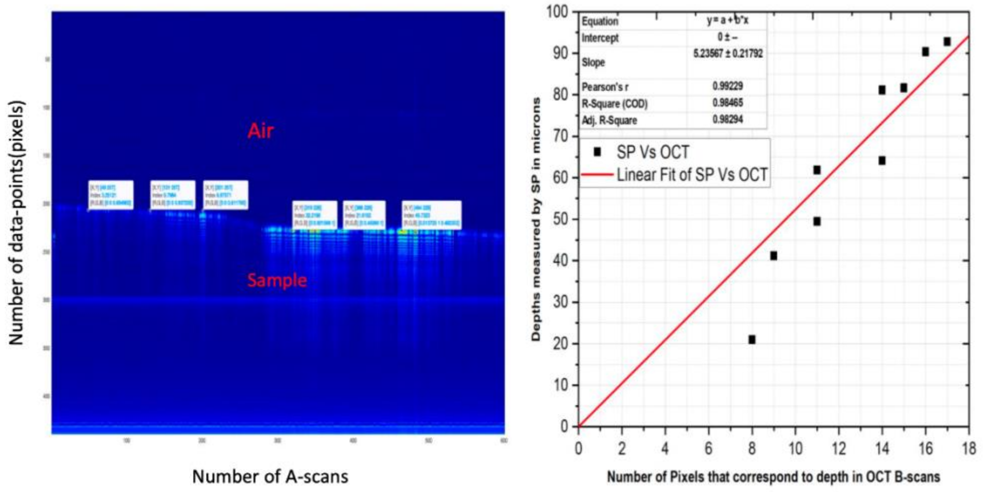


Figure 24. (a) Top view of OCT 3D image of the sample. (b) Top view of SP 3D image of the sample.

(c) Contrast-enhanced SP 3D image. (d) Registered image of the two images.



(a) (b)

Figure 25. (a) The number of pixels that corresponds to depth in this OCT B-scan is 21 (228-207). (b) Calibration curve for OCT

(g) Statistical analysis of the results

In the first part of the experiment, the correlation and agreement between the two measurement methods were assessed using the intra-class correlation coefficient (ICC), determining the significance of the difference between the mean values obtained by each method, and analyzing the Bland-Altman plots. In the second part, the average wear depths of the three different restorative materials were subjected to a one-way analysis of variance (ANOVA) with materials as the independent factor. Tukey's post hoc tests were performed to identify any statistically significant differences between and within the mean wear depths of the various restorative materials.

All statistical analyses were conducted at a significance level of 5% using Origin Pro, 2021 (Origin Lab Corporation, Northampton, MA, USA), and SPSS (IBM SPSS Statistics, USA, Version 28.0.0 (190)).

Results

(a) Comparison of wear depth measurement methods

The intra-class correlation coefficient (ICC) estimate and its confidence interval were calculated using SPSS with the following parameters: two-way mixed effects, k=2, and consistency. The results demonstrate excellent reliability between the two measurement methods (Table 15).

To assess the significance of the difference between the means, a Two-Sample t-test was employed. The mean wear depth measured by SP (69.81 μm) did not significantly differ from the mean wear depth measured by OCT (63.77 μm) (Table 17).

The level of agreement between the two methods was further analyzed using the Bland-Altman plot [13] (Figure 26).

Table 15. Intra-class Correlation Coefficient of SP and OCT measuring methods

Intra-class Correlation	95% CI Lower Bound	95% CI Upper Bound
0.99	0.979	0.995

Table 16. Descriptive statistics of SP Vs OCT measuring methods

	N	**Mean**	**Std. Deviation**	**Std. Error of the Mean**
SP measurements	30	69.81	11.74	2.14
OCT measurements	30	63.77	11.94	2.18

Table 17. Significance of difference between means for SP and OCT measuring methods

	t statistic	**DoF**	**Prob>|t|**
Equal Variance Assumed	-1.97	58.00	0.05315
Equal Variance NOT Assumed	-1.97	57.98	0.05315

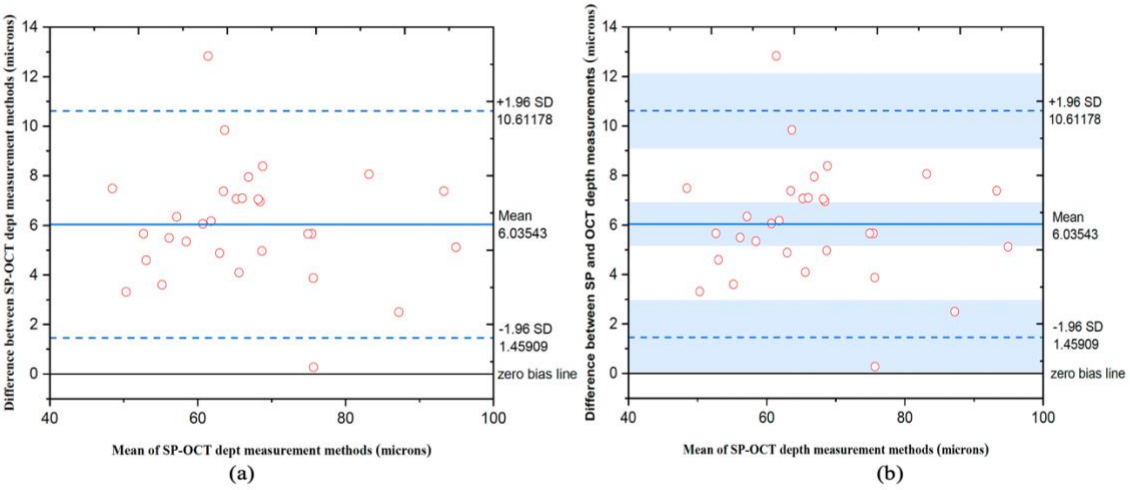


Figure 26. (a) Bland-Altman plot for SP-OCT measurement methods. (b) Same plot as (a), with the representation of CI limits for mean and agreement limits (shaded areas)

(b) Comparison of wear depths in the three different restorative materials

The results obtained from the second part of the experiment were subjected to one-way ANOVA and Tukey's post hoc tests for analysis. The ANOVA (F (2,87) =131.28, p=<0.001) indicated a statistically significant difference among the average wear rates of the three restorative materials (Table 19).

Further analysis using Tukey's post hoc tests (Tukey HSD) revealed that the average wear rate of amalgam (63.77±11.94, p=<0.001) was significantly different from that of the composite resin materials (Table 18). However, no statistical difference was observed between the average wear rates of the two composite resin materials (p=0.874).

Table 18. Descriptive statistics of the average wear rates of the three restorative materials

Material	N	Mean (μm)	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Amalgam	30	63.77	11.94	2.18	59.31	68.23
LV_Composite	30	22.61	12.21	2.23	18.05	27.17
HV_Composite	30	21.13	10.48	1.91	17.21	25.04

Table 19. ANOVA result of the average wear rates in the restorative materials

	Sum of Squares	DoF	Mean Square	F-Value	P-Value
Between Groups	35146.026	2	17573.01	131.28	<0.001
Within Groups	11646.046	87	133.86		
Total	46792.072	89			

Table 20. Multiple comparisons of the average wear rates in the restorative materials using the Tukey HSD test

Material (I)	**Material (J)**	**Mean Difference (I-J)**	**Std. Error**	**P-Value**	**95% Confidence Interval**	
					Lower Bound	**Upper Bound**
Amalgam	LV_Composite	41.16*	2.99	<0.001	34.04	48.29
	HV_Composite	42.64*	2.99	<0.001	35.52	49.76
LV_Composite	Amalgam	-41.16*	2.99	<0.001	-48.29	-34.04
	HV_Composite	1.48	2.99	0.874	-5.65	8.60
HV_Composite	Amalgam	-42.64*	2.99	<0.001	-49.76	-35.52
	LV_Composite	-1.48	2.99	0.874	-8.60	5.65

*The mean difference is significant at the 0.05 level

Discussion of results

Researchers have utilized OCT to investigate various dental problems, both in vitro and in vivo, such as periodontal disease, dental restoration, dental caries, tooth crack, and wear.

In this study, we initially evaluated the ability of OCT to measure wear in a dental restorative material, specifically Amalgam, by calibrating it with the standard method. We selected the SP as the gold standard because our focus was solely on the depth profile of the samples, as opposed to the subsurface profile. This distinguishes our work from previous studies where researchers compared OCT with various other measurement methods such as μ-CT, confocal laser scanning microscopy (CLSM), etc. In those studies, the Dentin-Enamel Junction (DEJ) served as a reference point for enamel thickness measurements since they lacked a mechanism to quantify wear other than relying on measurement apps like screen ruler, ImageJ, PixelStick, etc. Hence, they conducted their experiments using human teeth [15–18].

Furthermore, these measurement apps can introduce errors in the quantification of wear or enamel thickness. For instance, Algarni et al. examined the agreement between three different methods (polarization-sensitive OCT, μ-CT, and histology) for measuring enamel thickness. Their findings indicated that OCT measurements were significantly higher on average compared to μ-CT by 0.064 mm and had a discrepancy of 0.088 mm compared to histology measurements [15].

To quantify wear depth in our study, we employed image registration and calibration techniques, without the use of distance (depth) measuring apps. The Bland-Altman plot (Figure 26a) revealed that the limit of agreement ranged from 1.46 to 10.62 μm, with the OCT measurement deviating from the zero-bias line by 6.04 μm. We assessed the precision of OCT in evaluating dental wear against the SP by examining the 95% confidence interval around the mean difference (Figure 26b).

Although our study improved the accuracy and sensitivity of OCT measurements compared to Algarni et al., the zero bias line was not within the Confidence Interval (CI) of the mean. This suggests a significant systematic difference between the two measurement methods [15][19].

Additionally, our results demonstrated no significant difference between the means of the two methods (Table 17), in contrast to the findings reported by Algarni et al. [15] when comparing Co-Polarization OCT (CP-OCT) with μ-CT. The results indicated that OCT could evaluate the depth profile similar to an SP, given the excellent correlation and agreement (ICC = 0.99) between the two measurement methods. This finding aligns with the previous work of Alghilan et al. [16], where they employed CP-OCT and μ-CT to monitor the wear progression of natural human enamel slabs. Both methods exhibited excellent agreement in measuring enamel thickness on both natural (ICC = 0.98) and worn surfaces (ICC = 0.98).

In the second part of our study, we employed OCT to quantify the wear rates in three restorative materials: Amalgam, LV_composite, and HV_composite. These materials are commonly used for multi-surface restorations in posterior teeth [20]. Despite a decline in the use of amalgam, an extensive payer database revealed that 14% of direct restorations in 11.8 million patients were still performed using amalgam [22], indicating that some patients still prefer it. However, composite resin restorations remain popular for their excellent aesthetics and micromechanical bonding to teeth.

Our results indicated that the wear rate in amalgam is approximately three times higher than in composite resins. One contributing factor is that recent composite resin restorative materials incorporate nano-sized fillers that are uniformly distributed throughout the resin matrix (Table 18). This combination renders composite resin restorations more resistant to mechanical wear, especially in vitro experiments. However, in vivo applications involve a complex combination of factors, making it challenging to pinpoint a dominant cause of tooth wear [22]. Amalgam restorations, on the other hand, demonstrate better longevity than composite resins, particularly for posterior restorations, as most composite resin failures typically initiate at the bonding interface. Our results also indicated that LV_composite resin exhibits slightly higher mean wear than HV_composite, but no statistical difference was observed between the two groups (Table 20). This finding corresponds to the information provided in the manufacturer's scientific manual, as LV_composite has a lower filler weight percentage compared to HV_composite [23].

Our findings further support the notion that OCT is an excellent imaging system that can be utilized in dentistry. For instance, Otis et al. conducted the first in vivo study where they employed OCT to image both hard and soft dental tissues at high resolution. Their results demonstrated that the OCT system's resolution was capable of visualizing periodontal tissue contour, connective tissue attachment, and sulcular depth [9].

Although we have demonstrated that OCT is a viable option for dental imaging devices, researchers [11][8] have pointed out several reasons why the OCT system has not been widely adopted in clinical dentistry:

1. Limited availability of commercial OCT systems due to the high cost of components, resulting in only a few manufacturers producing commercial OCT devices.
2. Most OCT image analysis software and algorithms are still in the laboratory stage and not commercially available.
3. The scanning range of OCT needs improvement; the current scanning range is in millimeters, requiring multiple images to scan an entire lesion.
4. Different samples require different wavelength ranges. For instance, the buccal cavity contains both hard and soft tissues. A wavelength of 1550 nm is suitable for imaging hard tissue but may result in a poor image of the gingiva due to the soft tissue's absorption.

There are several benefits to using OCT for detecting dental wear. One of the main advantages is the dental practitioner's ability to track the wear of dental fillings and predict the risk of failure. Additionally, this new method of wear quantification would be easier, faster, and more accurate compared to the traditional impression/casting processes.

In conclusion, while the SP measuring method cannot be used clinically, it is accurate in estimating the surface profile of materials, and we have utilized it as a standard method for comparison against OCT in this study. The results we have presented demonstrate that OCT can be clinically employed in dentistry to measure tooth wear without relying on external length (depth) measuring applications. However, it is important to note that the comparison results presented here are derived from in vitro experiments and may not directly translate into in vivo applications.

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Chapter VII- Conclusion and Future work

Tooth wear is characterized by the irreversible loss of enamel, and excessive wear can pose a threat to a patient's well-being. In this study, we conducted a systematic review and found that the global prevalence of tooth wear with dentine exposure was 38%, with significant geographical variations among the included studies.

In clinical practice, quantifying and tracking wear progression is often a cumbersome and unreliable process. To address this, researchers have proposed the use of OCT. However, many rely on length or depth-measuring apps like ScreenRuler and ImageJ, which have shown to be inaccurate when compared to certain standard methods. In our work, we employed Optical Coherence Tomography with scaled NDFT image reconstruction to quantify and compare simulated wear on various restorative materials, eliminating the need for any external length or depth measuring apps.

In summary, this research has made significant contributions in the following areas:

1. Demonstrating, through a systematic review, that the global prevalence of tooth wear with dentine exposure is 38%.
2. Introducing the application of scaled NDFT OCT image reconstruction method, which utilizes redundant and non-uniformly spaced samples, to dental samples.
3. Performing the calibration of the OCT system by establishing a calibration curve based on wear measurements obtained from OCT and a standard method (Surface

profiler).

4. Quantifying and comparing wear on different restorative materials without the need for length or depth measuring apps.
5. Presenting an affordable OCT system that can be utilized in dental imaging.

However, it is important to acknowledge the limitation of this research, which is that the comparison results of wear in three different restorative materials are derived from in vitro experiments and may not directly translate to the oral environment.

Recommendations for Future Work

Although the results from this research have made the OCT closer to becoming a clinical imaging tool in dentistry, there are still some works to do. We will recommend the following for future works:

- The OCT sample arm could be redesigned into a hand-held or mouth guard probe for clinical use.
- The probe should contain a mechanical mechanism to make multiple sequential B-scans possible.
- An algorithm should be developed to automate the process from scanning to image reconstruction and depth or lesion quantification.