Wear 269 (2010) 930–936

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Short communication

Wear quantification of human enamel and dental glass–ceramics using white light profilometry

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ARTICLE INFO

Article history:
Received 30 March 2010
Received in revised form 6 August 2010
Accepted 19 August 2010
Available online 9 September 2010

Keywords:
White light profilometry
Wear quantification
Enamel
Dental glass–ceramic
Non-contact chromatic confocal

ABSTRACT

The aim of this study was to develop a protocol for quantifying wear using white light profilometry. Human molar cusps and glass–ceramic disc (Ceramco-3, Ceramco, USA) surfaces were digitised using a non-contact profilometer (Proscan-2000, Scantron, UK) with an S16/3.5 white light sensor (Stil-S.A., France), before and after *in vitro* wear testing. Digitised images were superimposed using the dedicated software (Proform, Scantron, UK). Superimposed images were further processed in Proscan-2000 software to eliminate interferences with calculation of wear quantification parameters (volume, mean-height loss) by isolation of the worn area. Scanning repeatability and operator uncertainty introduced systematic errors that were also evaluated. The elimination of the areas surrounding the wear pattern produced significantly improved results for tooth ($p<0.05$) and glass–ceramic disc ($p<0.001$) mean-height loss. Tooth volume loss accuracy was improved by 6.83% while disc volume loss was adequately calculated using the software's automated tool. Operator uncertainty tests produced mean (SD) mm^3 differences of 0.0040 (0.0023) for tooth specimens and 0.0013 (0.0007) for glass–ceramic disc specimens. Scanning repeatability tests produced mean (SD) mm^3 differences of 0.0024 (0.0007) for tooth specimens and 0.0030 (0.0015) for glass–ceramic disc specimens. The improved and repeatable measurements obtained may suggest a similar approach to be beneficial for similar applications and materials.

1. Introduction

Tooth wear is the surface material net loss of a tooth under function. Tooth wear can incorporate different processes frequently occurring in combination that lead to material loss such as erosion, attrition and abrasion [1]. The latter is caused by contact with a material other than tooth [2]. Distinguishing amongst these processes may be difficult in practice and for this reason the term wear is used to describe material loss [3]. Interest in quantification of the material loss (wear quantification) of dental materials and dental hard tissues is evident by the plethora of studies in the literature [4–7]. Wear quantification methods for measuring material loss after *in vivo* or *in vitro* wear tests include measuring weight [8], height [9], mean height, [10,11] and volume [10,12] material loss parameters. Volume and mean height parameters provide the most clinically relevant information as they can be linked to cuspal structure loss and, ultimately, to facial height loss [13]. Wear quantification methodologies that can provide reliable and repeatable results are thus essential. While surface matching and difference detection software are commercially available for *in vitro* wear quantification, algorithms have also experimentally been developed [14] and applied in quantification of erosive wear *in vivo* [5]. Ongoing research highlights that these resources need to be tested and understood before application in dental studies as their infallibility should not be taken for granted [14]. Clinical wear evaluation studies are extremely time consuming and require expertise in patient selection, data collection and analysis [6]. *In vitro* wear evaluation is therefore a useful alternative especially when comparing new materials.

The *in vitro* wear quantification process usually requires the employment of a method that can make an accurate topographical representation of the surfaces of interest before and after wear testing. Methods that have been employed for *in vitro* wear quantification include mainly three types of sensors for scanning and subsequent digitisation of surfaces. These include mechanical sensors (contact) [15], and non-contact sensors such as laser [10] and white light [16]. All three sensor types have been found to be suitable for the quantification of wear facets in a systematic study by

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doi:10.1016/j.wear.2010.08.019

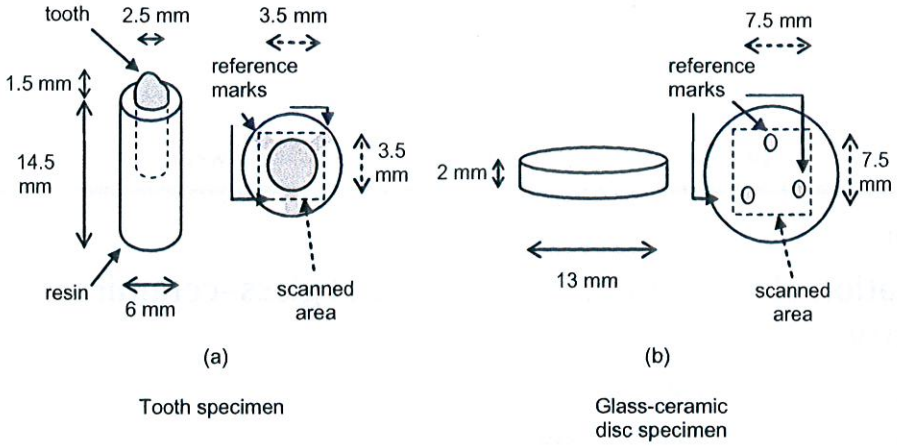

Fig. 1. Schematics of the (a) tooth and (b) glass–ceramic disc specimens.

Heintze et al. [6]. Many studies have used white light non-contact profilometric techniques for quantification of dental wear related phenomena such as erosion [17] and/or abrasion [6,16,18]. The information provided in most of the studies is usually limited to sample type and testing method while parameters used for the scanning (e.g. sensor, sampling rate) and the rationale behind the choice are not discussed.

White light profilometry utilizes accurate distance measuring sensors. These sensors incorporate special lenses that can split the light beam of a polychromatic (white) light source into its constituent wavelengths [19]. Each wavelength can only be sharply focused on a point that lies at a specific distance from the sensor, thus creating a continuum of monochromatic imaging points. The distance sensing ability of the sensor is enabled by matching the central wavelength of the reflected beam to the exact height of the focused point via a spectrometer. A microtopographic image is then constituted by raster scanning across the desired specimen surface [19,20]. Applications of white light sensors include industrial process control, reverse engineering and as high precision research tools. These non-contact sensors can provide analysis of shape and texture, microtopography and microform as well as roughness measurements [21].

The aim of this study was to design a novel protocol for quantification of material loss after wear testing of human enamel versus glass–ceramics using white light profilometry. The protocol was designed to quantify the volume and mean height loss of the enamel and glass–ceramic material as a result of the wear testing, using specialized software. The step size selection process, operator introduced uncertainty and scanning repeatability were investigated. The null hypothesis (Ho) tested was: the Automated measurements generated by the software for volume and mean height loss were not significantly different from the values obtained by the proposed experimental methodology.

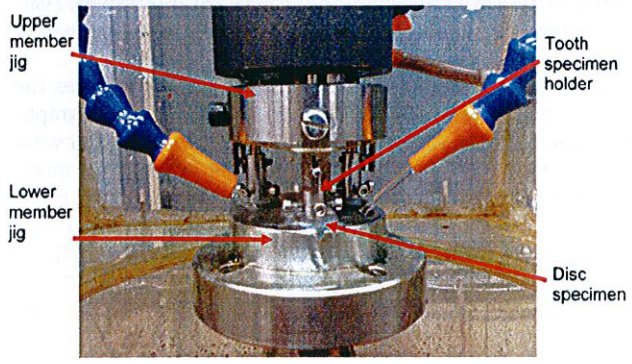

Fig. 2. Wear testing apparatus.

2. Materials and methods

2.1. Wear testing specimen preparation

2.1.1. Tooth specimen preparation

Freshly extracted human adult molar teeth were collected from the Department of Oral and Maxillofacial Surgery (Institute of Dentistry, Barts and The London School of Medicine and Dentistry) and stored in a 30% water/70% ethanol solution in a tissue bank (Medical Ethics REC: 06/Q0603/98). The teeth were visually screened by the same operator under a microscope (Wild M3B, Heerbrug, Switzerland) to exclude those with pointed configurations, demineralisations or surface defects [22]. Eight individual cusps were sectioned in the form of cylinders using a 2.75 mm inner diameter core drill (UKAM Industrial Superhard Tools, Valencia, USA) under water lubrication. The selected tooth cylinders were embedded in photo-curing resin (Palatray, Heraeus Kulzer, UK) using a custom made hollow cylinder PTFE mould (6 mm inner diameter x 14.5 mm height) (Fig. 1a). Three reference marks were made on the top surface of the resin stub containing the embedded tooth (Fig. 1a) by pressing a wax tool tip against the uncured resin. The reference marks acted as reference points for accurate alignment of the digitised surfaces before and after wear testing. The stub was then light cured for 5 min from different directions (3M ESPE Elipar™ Freelight™, Germany).

2.1.2. Glass–ceramic specimen preparation

Eight glass–ceramic disc specimens were constructed by mixing Ceramco 3 (Batch No. 02111576, Dentsply, Ceramco, Burlington, USA) dentine powder (0.96 g) with 0.3 mL of modeling liquid (C.H.B 24066, Vita Zahnfabrik, Germany) and transferring to a hollow cylinder steel mould (16 mm inner diameter) with a plunger. The mould was gently vibrated to remove excess moisture from the slurry and tissue dried (30 s). The powder slurry was compacted at 1 kg × 10^3 for 1 min and then transferred to a dental porcelain furnace (Multimat MCII, Dentsply, Weybridge, UK) and sintered according to manufacturers' instructions using 1 dentine and 1 glaze firing cycle. The disc specimens (2 mm thickness) were then wet lapped on one side with P600 SiC paper to achieve flatness and standardize the test surface. Three hemispherical reference marks forming the points of a triangular area in which the wear test was to be carried out were made on the glass–ceramic disc

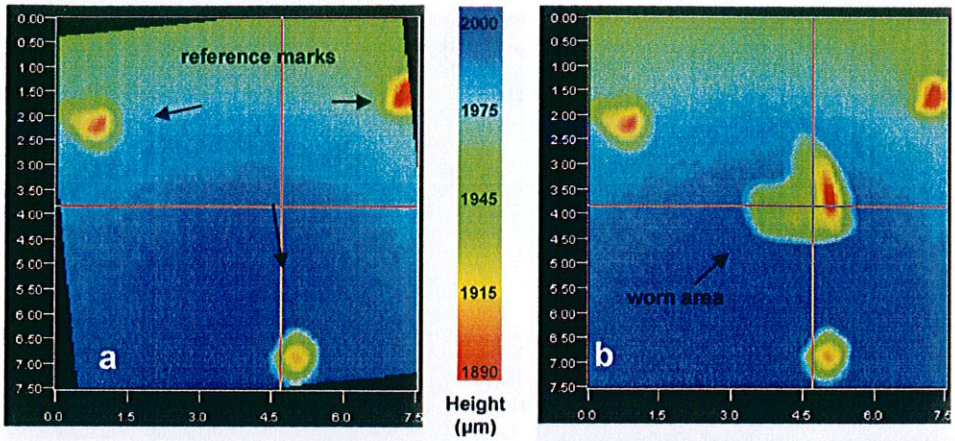

Fig. 3. Digitised glass–ceramic disc surfaces (a) before and (b) after wear testing.

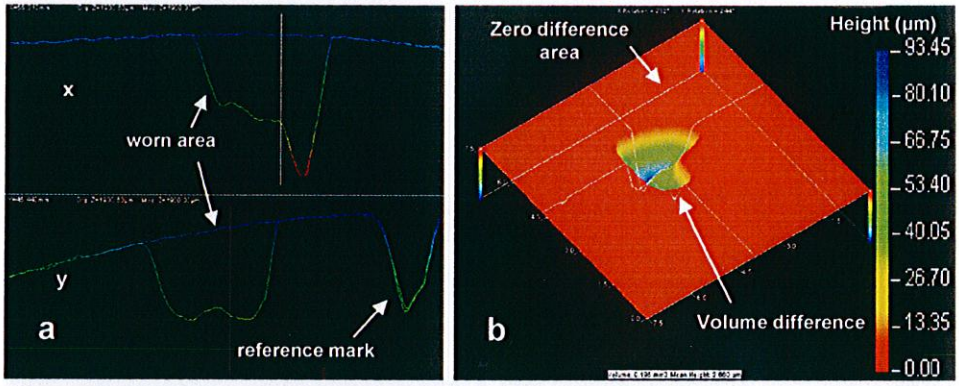

Fig. 4. (a) Digitised glass–ceramic disc cross sectional (x, y) fit overview and (b) superimposed 3D difference view.

surfaces using a pointed dental stone followed by a dental rubber bur (Fig. 1b). Specimens were then cleaned in an ultrasonic bath with aqueous detergent solution (Decon 90, Decon Laboratories Ltd., E. Sussex, UK) for 10 min and then washed with water.

2.1.3. Wear testing

All glass–ceramic disc specimens were stored in deionized water while enamel specimens were stored in a 30% water/70% ethanol solution for 24 h before testing. Glass–ceramic discs and enamel specimens were fixed into specially designed holders (Fig. 2) on the

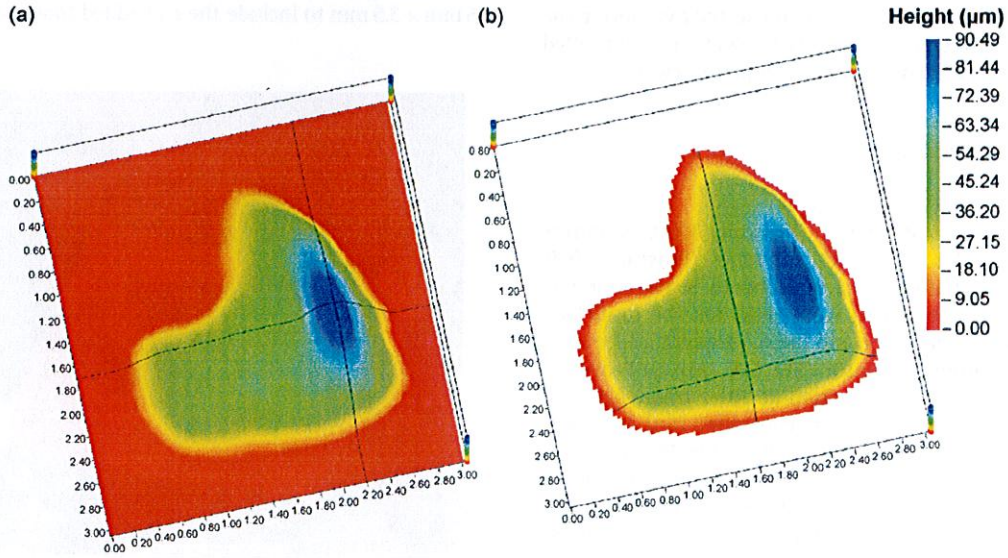

Fig. 5. (a) Cropped difference view for glass–ceramic disc volume loss calculation. (b) Isolated glass–ceramic disc worn area for mean height loss calculation.

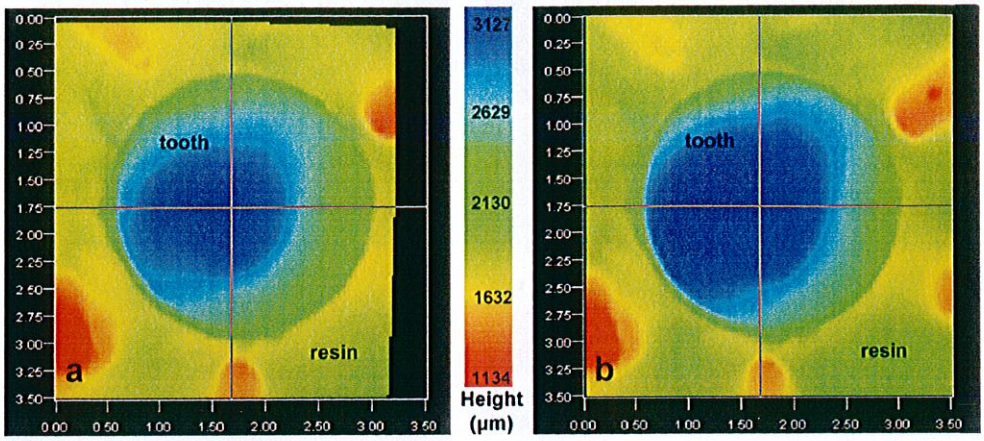

Fig. 6. Digitised tooth surfaces (a) before and (b) after wear testing.

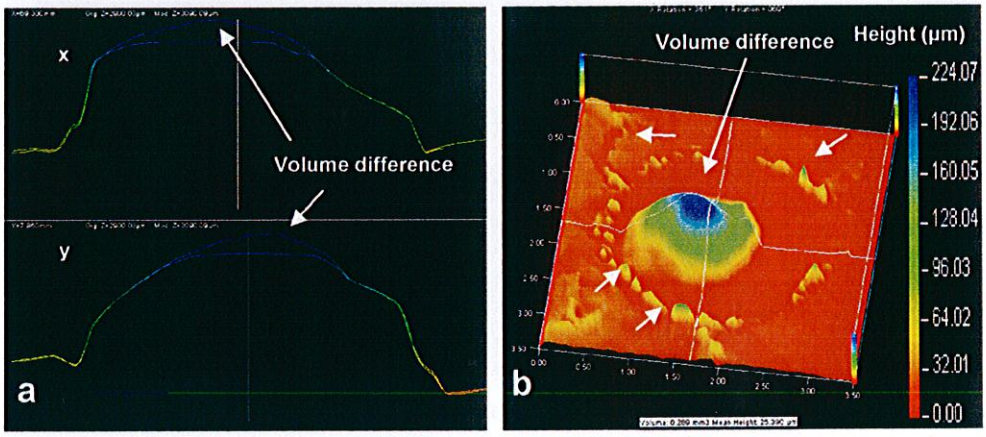

Fig. 7. (a) Tooth cross sectional (x, y) fit overview and (b) superimposed 3D difference view showing irregularities and peaks (arrows) interfering in the volume/mean height loss calculation.

upper and lower members of a servo-hydraulic test frame (Bionix 858, MTS, Minnesota). The opposing glass–ceramic disc and enamel specimens were subjected to 300,000 simulated masticatory cycles at a rate of 2 Hz under a continuous flow of deionized water (37 °C). Specimens were loaded with a load of 13.5 N each, by operating the axial shaft under displacement control on the axial plane. This was followed by a lateral excursion movement exerted by rotating the axial shaft under displacement control by 1.5 degrees. A controlled cuspal contact time (0.25 s) was used to complete a cycle.

2.2. Scanning method development

2.2.1. Scanning equipment and parameters

A non-contact 3D profilometer (Proscan 2000, Scantron, Taunton, UK) and the dedicated software (Proscan 2000, ver.2.1.8.8+ software, Proform ver.1.41 software, Scantron Industrial Products Ltd., Taunton, UK) were used for the tooth and glass–ceramic surface digitisation and the subsequent image analysis. The S16/3.5 Chromatic sensor (Stil S.A., Aix-en-Provence, France) was used for all scans operated at 30 Hz frequency (low scanning speed) through a CHR-150 controller (Stil S.A., Aix-en-Provence, France) that was connected to the Proscan 2000 profilometer. This sensor has a 3.5 mm measuring range and a 75 nm axial resolution. Dark background measurement was performed prior to each scanning session to ensure maximum sensor sensitivity to reflected light. The step size for the scans was selected according to Section 2.2.2.

2.2.2. Step size selection

A custom made jig was constructed to fit on the Proscan 2000 stage which allowed the repositioning of tooth and glass–ceramic disc specimens before and after wear testing. A series of pilot scans on a tooth and a glass–ceramic disc specimen was conducted. The scanning area of the tooth specimen surface was limited to 3.5 mm × 3.5 mm to include the embedded tooth section (Fig. 1a).

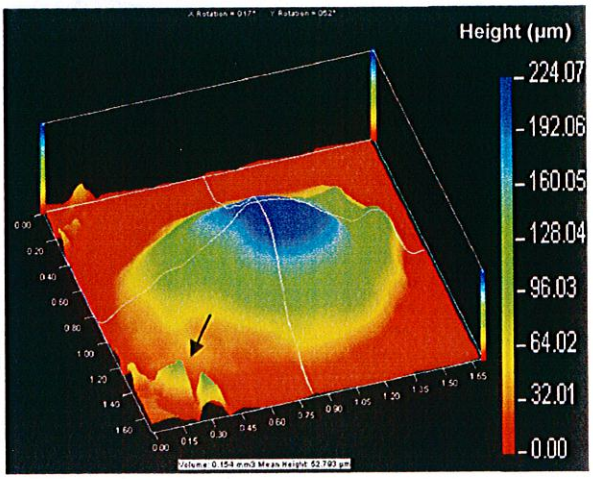

Fig. 8. Cropping of the digitised tooth specimen area with unwanted peaks included.

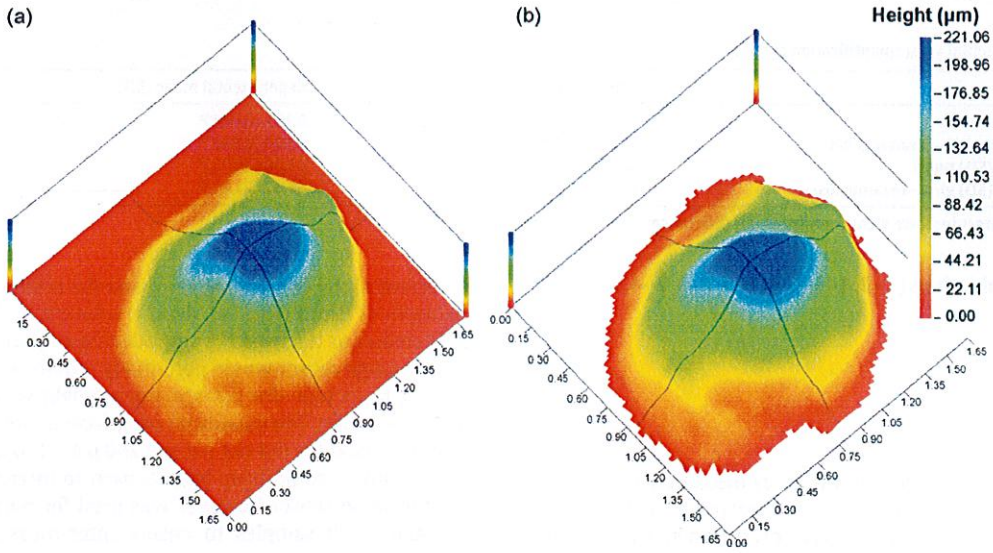

Fig. 9. (a) Peaks eliminated and a zero area inserted around the difference view for tooth volume loss calculation. (b) Isolation of the tooth wear area for mean height loss calculation.

The scanning area on the glass–ceramic disc specimen surface was limited to 7.5 mm × 7.5 mm to include the area to be worn (Fig. 1b). The specified areas of the tooth and the glass–ceramic disc specimens were scanned using five step sizes (10, 20, 30, 50 and 100 μm) in both *x* and *y* directions prior to simulated wear testing. The tooth specimen surface was then ground using wet P1000 and P2400 SiC papers on a lapping machine (20 s on each paper, 300 rpm) to simulate the wear process, then washed with water and cleaned with ethanol. The disc specimen was subjected to a pilot wear test (details in Section 2.1.3), then washed with water and surface cleaned with ethanol. Specimens were repositioned on the scanner using the custom jig and the same series of scans were carried out. The resultant digitised images were superimposed using the Proform software (ver.1.41, Scantron, Taunton, UK) to measure the volume loss in respect to varying step size.

2.2.3. Wear quantification method and measurement improvement test

All tooth and glass–ceramic disc specimen test surfaces were scanned before and after wear testing using the optimal step sizes (teeth: 20 μm, glass–ceramic discs: 30 μm) selected previously. The digitised test surfaces before and after wear testing were superimposed (Proform ver.1.41, Proscan 2000 ver.2.1.8.8+ software, Scantron, Taunton, UK) to quantify the total volume and mean height loss. Filters (Proscan 2000 ver.2.1.8.8+ software) were applied to all tooth (warpage 2) and glass–ceramic disc (warpage 3) digitised surfaces. This was performed to separate the long wavelength (low frequency) shape associated information from the short wavelength (high frequency) roughness associated information prior to the superimpositions.

The series of steps followed for the wear quantification of the glass–ceramic disc specimens is shown in Figs. 3–5 namely; before and after wear profile check, superimposition and graphical wear quantification. The shading in all figures illustrates height gradient. The three reference marks made on the disc surface (Fig. 3a and b) were used for alignment of the surfaces before and after testing. The surfaces were superimposed (Fig. 4a and b) and the region with the volume difference was cropped to a square area of 3 mm × 3 mm. At this stage Automated measurements are provided from the software for the volume and mean height loss and these were recorded as the "Automated" set of data. The superimposed file (difference view) was then saved and opened in the Proscan software where the volume tool was used to measure the values. The difference view was then further processed in Proscan software to isolate the worn area (Fig. 5a and b). The file (*x*, *y*, *z* data) was then exported in Excel format and the height values (*z* values) were averaged to generate the mean height loss for each specimen. These values were recorded as the "Experimental" data set.

For the tooth specimens (Figs. 6 and 7), the difference view from the Proform software was cropped as closely as possible to the worn area (Fig. 8) and the volume/mean height loss measurements provided by the software were recorded as the "Automated" set of data. It was then further processed in the Proscan software to delete unwanted areas around the worn area that interfered with volume calculation (Figs. 7 and 8b). The deleted areas were then replaced with a zero height area (Fig. 9a) to enable the final volume loss determination by the Proscan software. Mean height calculation was then performed as for the disc specimens (Fig. 9b). The values recorded at this stage were recorded as the "Experimental" set of data.

The "Automated" and "Experimental" data sets created for volume and mean height loss of human enamel and glass–ceramic were then compared using individual *t*-tests to evaluate statistical differences ($p < 0.05$).

2.2.4. Operator uncertainty and scanning repeatability tests

Superimpositions were carried out (5×) following the developed protocol on a tooth/glass–ceramic disc pair, before and after wear testing to evaluate the wear quantification testing process and operator uncertainty. The volume loss values from the individual scans (1–5) were then subtracted in all possible combinations (1–2, 1–3, 1–4, 1–5, 2–3, 2–4, 2–5, 3–4, 3–5, 4–5) and the differences averaged. Scanning repeatability was also evaluated by repeated (5×) scanning of a tooth and a glass–ceramic specimen. The volume difference between the scans was measured by superimposing scans

Table 1
Step size selection results.

Step size (μm)	Tooth volume loss (mm³)	Disc volume loss (mm³)
10	0.226	0.161
20	0.224	0.161
30	0.225	0.161
50	0.218	0.158
100	–	0.151

Table 2
Automated and Experimental wear quantification results.

Measurement	Automated mean (SD)	Experimental mean (SD)	% Difference
Volume loss mm^3 (SD) teeth	0.206 (0.072)[a]	0.192 (0.066)[a]	6.83
Volume loss mm^3 (SD) glass–ceramic discs	0.184 (0.042)[a]	0.184 (0.042)[a]	0
Mean height loss μm (SD) teeth	48.42 (16.63)[a]	65.50 (20.58)[b]	27.9
Mean height loss μm (SD) glass–ceramic discs	19.85 (5.58)[a]	67.62 (21.01)[b]	69.4

Different superscript letters indicate significant ($p < 0.05$) differences between mean values tested.

in all possible combinations (1–2, 1–3, 1–4, 1–5, 2–3, 2–4, 2–5, 3–4, 3–5, 4–5).

3. Results

3.1. Step size choice

The results of the volume loss values as measured at different step sizes on a tooth and a glass–ceramic specimen can be seen in Table 1. For both the tooth and the glass–ceramic disc, there is very little or no difference in the measured volume loss at 10, 20 and 30 μm step sizes. For the glass–ceramic disc specimen the measured volume loss at 50 and 100 μm step sizes shows a reducing trend. For the tooth specimen the measured volume loss at 50 μm was also reduced in respect to the 10, 20 and 30 μm step size measured volume loss. At 100 μm the calculation of the volume loss was not facilitated for the tooth specimen due to insufficient detail to aid the superimposition process and scanning artefacts present. The selected step size for tooth specimens was 20 μm while for the glass–ceramic specimens it was 30 μm.

3.2. Operator uncertainty and scanning repeatability results

The results for operator uncertainty produced a mean (SD) difference between measured volume loss values of 0.0013 (0.0007) mm^3 for the glass–ceramic disc and of 0.0040 (0.0023) mm^3 for the tooth specimen. The result for scanning repeatability produced a mean (SD) volume difference between scans of 0.0024 (0.0007) mm^3 for the tooth specimen (compared area 1.6 mm × 1.4 mm) and of 0.0030 (0.0015) mm^3 for the disc specimen (compared area 3 mm × 3 mm). Comparing the acquired repeatability and operator induced errors with the mean volume values of the experimental protocol measurements (Table 2), we obtain errors ranging 1.25–2.08% for teeth and 0.7–1.63% for discs.

3.3. Automated and Experimental wear quantification results

The results for the measurements acquired via the Automated and Experimental methodologies are shown in Table 2. The Automated software measurements adequately calculated disc volume loss and for that reason the mean values measured via Automated and Experimental protocols were equal. A mean volume loss overestimation of 6.83% was measured when applying the automated protocol on teeth, however no statistically significant difference ($p > 0.05$) between Automated and Experimental values was identified and thus Ho was accepted. There was a significant difference between the means for both tooth ($p < 0.05$) and glass–ceramic disc ($p < 0.001$) mean height loss values between Automated and Experimental measurements. Ho was rejected in this instance.

4. Discussion

The sensor chosen for the wear quantification measurements in this study was mainly chosen based on its measuring range (3.5 mm) and its high axial resolution (75 nm). The axial distance to be measured on the teeth samples in order to include the tooth cusp, the surface of the embedding resin and the reference marks was a maximum of 2 mm (Fig. 1a). Axial resolution in this type of sensors increases as the working range decreases [20]. Use of a smaller working range sensor would potentially require axially segmented scanning to include the full specimen height without significant gain in resolution. The maximum wear facet depth recorded on the glass–ceramic discs did not exceed 250 μm, thus a lower working distance sensor could have been chosen to increase axial resolution; the same sensor however was used for both glass–ceramic discs and tooth samples to ensure inter-measurement consistency.

The sampling rate of 30 Hz was chosen after a series of scans at all available frequencies (1000, 300, 100 and 30 Hz) which revealed that the slower the sampling rate, the less missing data appeared on the scans. The scans at 30 Hz eliminated missing data almost completely which whenever present were interpolated using the Proscan 2000 software. The slow sampling rate adopted was thus mainly dictated by the reflectivity of glass–ceramic/tooth samples both being translucent (scattering surfaces) [20]. Remaining missing data generally appeared either in 90 °C angles (e.g. areas between the embedding resin and the cusp cylindrical walls) or in locally high sloped surfaces. The latter may be attributed to the limitation of the sensor itself as its specifications include a maximum angular slope of 22 °C for specular surfaces, although this can be increased up to 80 °C for scattering surfaces [20]. Laser techniques, although much faster, require either coating the surfaces to be scanned or the fabrication of plaster replicas [6]. In contrast to laser techniques, white light Profilometry enabled the actual specimens' surfaces to be digitised potentially introducing less systematic errors in the acquired measurements.

The S16/3.5 sensors' lateral resolution (x, y) is quoted as 4 μm [23], therefore the step sizes investigated (10, 20, 30, 50 and 100) are well within the sensor's capabilities. The wear testing setup used in this study and most of the parameters (no of cycles, applied force, cuspal lateral excursion) were based on a setup used previously by Magne et al. [15], where the artificial oral simulator of De Long [24] was utilised. De Long [24] correlated wear results over a number of 250,000 cycles in his simulator with 1 year of *in vivo* mastication [25,26]. Magne et al. [15] quantified volume and mean height loss of human enamel and dental glass–ceramics, using a tungsten carbide contact sensor and a considerably lower x, y spatial resolution (50 μm × 100 μm), with results in the same range as the present study. Kramer et al. [11] reported that 10–25 μm step sizes can lead to reliable results with mechanical (contact) sensors. A resolution of 4 μm × 4 μm x, y of a white light sensor was found to be in good agreement to a >30 μm × 30 μm x, y resolution of a laser sensor [6], when both were applied to quantify volume loss in the same glass–ceramic and composite disc specimens. Hara and Zero [17] used a step size of 10 μm × 100 μm (Proscan 2000) to investigate the erosive potential of beverages on enamel. The 10 μm step size on teeth was not selected as it produced images that even after the application of the warpage filter were "noisy" leading to the application of a higher warpage filter to separate the roughness related information. The selected step sizes of 20 μm × 20 μm for tooth and 30 μm × 30 μm for glass–ceramic disc samples are therefore selected and are in the range suggested in the literature for similar applications and materials.

The volume loss figures of glass–ceramic disc specimens (Table 1) could be correlated to weight loss of the specimens using measured glass–ceramic density values. Considerations for varying glass–ceramic density should be then taken into account as a result of varying porosity [27] and a careful calibration protocol could be devised to ensure minimal systematic error involvement (e.g. balance calibration, standardized weighing conditions). This calibration would give a useful check for the data presented in Table 1. A calibration protocol for enamel specimens would however be more problematic. Tooth enamel density varies significantly from one tooth to another and also within the same tooth from the surface towards the amelodentinal junction (3.0–2.84 g/ml) [28]. Standardising weighing conditions (e.g. desiccation) could also influence the integrity and the wear characteristics of the tooth specimens.

The Automated measurements (Table 2), significantly ($p < 0.05$) underestimated the mean height loss in both tooth and glass–ceramic discs, supporting the use of the experimental protocol. In particular, 27.9% less mean height tooth loss and 69.4% less mean height disc loss was measured via the Automated regimen. The very satisfactory fit achieved on the disc samples resulted in an (almost) zero difference area around the wear facets (Fig. 4b). There was thus no need to delete the area around the disc wear facets for the volume calculation. This explains the absence of difference for the mean volume loss values measured on discs, via both the experimental and automated procedures (Table 2). The only difference in procedure is that the automated disc volume loss values were measured by the Proform software and the experimental from the Proscan software. This demonstrates the good agreement between the two different pieces of software. To limit any potentially systematically induced error, our protocol standardisation was limited to a 3 mm × 3 mm area which was ample to include the wear area. The apparent overestimation of the tooth volume loss by the Automated measurements (Table 2), failed to differentiate ($p > 0.05$) from the Experimental measurements, suggesting that the experimental protocol may not provide an added benefit in the volume loss calculation. In the present authors' opinion, although no significant difference was detected, exclusion of volume from areas around the area of interest (Fig. 8) was preferable. A potential error source is the accuracy of the utilized sensor. The accuracy of white light sensors is continuously being improved to achieve sub-micron levels (tested maximum linearity error for the S16/3.5 sensor is 0.4 μm [23]). The accuracy of measurements is thus much more likely to be affected by systematically induced errors and should therefore be considered in wear quantification protocol designs.

5. Conclusions

The proposed methodology was useful in the quantification of material loss after wear testing of human enamel and dental glass–ceramics, by improving the mean height loss calculations compared to Automated measurements. The repeatability of the measurements obtained suggests a similar approach could be beneficial for similar applications and materials in Medicine and Dentistry.

Acknowledgements

The authors acknowledge the financial support from St. Bartholomew's and The Royal London Charitable foundation (RAB05/PJ/06). The authors would also like to express their appreciation to Paul Adams, Tim Tuckey and Adam Henwood (Scantron, UK), Yael Cohen-Sabban (Stil SA, France) for the useful discussions and Bill Godwin and Vins Ford (School of Engineering and Materials Science, QMUL, UK) for their help in the wear jig design and the testing with the MTS 858 Bionix system.

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