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Title Page

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Title: The Sensitivity of Digital Intraoral Scanners at Measuring Early Erosive Wear.

Key Words: Tooth Wear, Tooth Erosion, Diagnostic Imaging, Dental Technology

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Abstract

Objectives: To investigate the sensitivity of intraoral scanners to quantitatively detect early erosive tooth wear.

Methods: Natural buccal enamel samples were mounted in acrylic and scanned at baseline with an intraoral scanner (*3M True Definition Scanner, 3M, USA*). Samples were then exposed to 0.3% citric acid pH 3.2 at intervals of 10 minutes up to a total of 120 minutes and scanned after each exposure resulting in analysis of 13 datapoints per sample. Each scan was aligned with the baseline and data points super-imposed using an iterative closest point (ICP) algorithm on the acrylic surfaces (Geomagic Control Software, 3Dsystems, Darmstadt, Germany). Wear was measured using maximum profile loss, average profile loss and volume change. Data were normally distributed and Pearson correlations between erosion time and wear measurements assessed.

Results: After each 10-minute exposure until 120 minutes, maximum profile loss (μm) increased from 33.4 to 72.8 μm, average profile loss from 9.1 to 18.6 μm. Wear correlated with increasing acid exposure for both maximum profile loss wear ($r=0.877$ $p<0.001$) and average profile loss ($r=0.663$ $p=0.019$) respectively. Volume measurements were inconsistent at this level of wear.

Conclusions: Using scan data obtained from the intra oral scanners (IOS), increasing step height changes were observed with increasing exposures to acid. This study indicates there is potential of scans taken with an IOS to be used to detect early erosive tooth wear. However, precision was low suggesting limitations for minimal changes.

Clinical Significance: Although sub-visual wear was detected by intra-oral scanners on natural enamel surfaces, the accuracy was not sufficient to reliably diagnose that wear had occurred and interpretation of measurements should be done with caution. However, these results may be promising for detecting wear at more advanced stages.

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1. **Introduction**:

The ability to diagnose and monitor early erosive tooth wear has proven challenging, both clinically and epidemiologically [1]. The use of tooth wear indices, [2] study casts, [3] and clinical photographs [1] are currently used within a general practice setting to monitor tooth wear. However, each method suffers from inherent limitations. Tooth wear indices are subjective [4], non-quantitative, and lack the sensitivity [5] to detect small changes in dental hard tissues. Although the Basic Erosive Wear Examination (BEWE) is being increasingly adopted, other tooth wear indices are being used [6,7] making comparison among patients is difficult. Similarly, study casts and clinical photographs lack sensitivity [8] whilst study casts also suffer from errors introduced by dimensional changes in impression materials [9] and dental stones [10]. With the increasing prevalence of erosive tooth wear [11,12] and lack of a quantitative method for monitoring tooth wear new approaches are required.

Previous studies have taken impressions at separate epochs, poured the impressions in dental stone and scanned the stone casts with profilometry [13–22] to create a data set which can be analysed for changes over the intervening time period. However, the associated specialised equipment cost, and scanning time of each cast limits this method to a university setting. Within the primary care setting, intra oral scanners (IOS) are becoming more common place within dental clinics. They digitally capture the dentition and may provide a suitable means of

quantitively monitoring erosive wear clinically. One study observed that scanned casts better discriminated change compared to visual analysis [23]. These findings were confirmed with another study comparing scanners to a visual assessment using the Basic Erosive Wear Examination (BEWE) [4]. The only study to investigate micron loss of enamel using 37% phosphoric acid etching gel applied to half of each crown for a period of 1, 5 and 10 minutes and compared to the other half isolated with a rubber dam to provide an area of reference for alignment [24].

There are a lack of studies investigating the use of IOS's to measure early erosive tooth wear or indeed any other type of tooth wear. The aim of this study was to investigate the ability of an intraoral scanner to quantitatively detect early erosive tooth wear. Our null hypotheses states that wear measurements on natural enamel surfaces will not be correlated with increasing acid exposure time when scanned with an intra oral scanner (*3M True Definition, 3M, USA*).

2. Materials and Methods

Extracted caries-free human molars were collected (n=8, REC ref: 12/LO/1836) and sterilised in Milton's solution (*Proctor & Gamble, USA*) for a minimum of three days. The buccal surface was sectioned using a water-cooled diamond wafering blade (*XL 12205, Benetec Ltd., London, UK*) at 100 RPM with a weighted force of 150g and then placed in a custom silicone mould and mounted in cold cure acrylic (*Protemp™, 3M, USA*). Each sample was based in acrylic measured 8mm (D) × 21.5mm (W) × 24mm (L). Samples were cleaned using a manual tooth brush, followed by a 15-minute ultrasonic bath and then wiped with ethanol.

The samples were then prepared for scanning by coating the surfaces with a light dusting of titanium oxide scanning spray (high resolution scanning spray, 3M, USA) using the powdering

gun positioned 2cm from the surface, as per the manufacturer's instructions. Each sample was then individually scanned (*3M True Definition, 3M, USA*), and the number of data points recorded on the enamel surface was doubled using the enhanced resolution capture. All scans were performed by a clinical research student with experience of performing laboratory experiments with the IOS. Repeated pilot experiments were performed initially in the absence of any wear to assess operator error and minimise standard deviations prior to the experiment.

Analysis was performed on these to capture the baseline error of the process in the absence of wear. Samples were agitated in deionised water for 10 minutes using a mini orbital shaker (*Stuart Scientific, Mini Orbital Shaker S05, Bibby*) set at 62 RPM, held in a weighted acrylic jig. Samples were air dried with a 3 in 1 dental syringe (Dentsply, UK) and then coated in powder and rescanned.

The dietary acid was formulated with 3g of anhydrous citric acid powder (*99%; Sigma Aldrich, Haverhill, UK*) added to 1 L of deionised water to make up a 0.3% citric acid solution. A homogenised solution was achieved with a magnetic stirrer and aqueous sodium hydroxide (1M) was added until a pH reading of 3.2 was obtained.

To assess wear, each enamel sample was immersed and stirred at 62rpm in citric acid (0.3% pH 3.2) for 10 minutes using the mini orbital shaker (*Stuart Scientific, Mini Orbital Shaker S05, Bibby*). After each 10-minute immersion cycle, the samples were scanned using the intraoral scanner and the same cleaning protocol was used. This cycle of 10-minute acid immersion and scanning was repeated until there was a total exposure time of 120 minutes or 12 more measurements per sample.

Analysis was carried out using Geomagic Control 2014.2.0: 64 Bit Edition (2014.2.0.1765) (*3Dsystems, Darmstadt Germany*) by comparing change to the acrylic surfaces around the sample. Alignment was achieved using an iterative closest point (ICP) technique. The baseline dataset was compared to each time interval scan by aligning 1000 data points randomly selected by the software. The alignment was then finely adjusted using 5000 randomly selected data points and the rigid transformation matrix saved. This matrix was then applied to the full post-experimental scan. The software was used to calculate, the maximum point loss on the surface and the average loss across the entire surface. Maximum loss is the largest measured decrease in profile whilst average loss is the mean profile decrease measured over the whole surface.

To ensure the same area and surface was analysed for each digital scan, after alignment, all the scans were sectioned together leaving only the enamel tooth surface. The scans taken after the samples had been immersed in deionised water for 10 minutes were used as the baseline scans.

Data were analysed using SPSS version 24 software (*IBM SPSS Statistics for Windows, Version 22.0; IBM Corp, New York, US*) for normality, using Sharpiro-Wilks test and visually using boxplots and histograms. All data were normally distributed. Spearman's correlation co-efficients were calculated between acid exposure and each of the above metric. Correlation between profile changes and volume loss was also calculated. Interpretation of Spearman's correlations were used according to Hinkle et al. [37] whereby 0-0.3 indicated a negligible correlation, 0.3-0.5 a low correlation, 0.5 to 0.7 a moderate correlation and above 0.7 to be a high correlation. Significance was inferred at $p<0.05$

3. **Results**

The error of the operator and analysis process was 22.6μm (±10.3) for the maximum loss and 5.5 μm (± 3.3) for the average loss.

After 120 minutes immersion, the maximum profile loss increased from 33.4 (±10.3) to 72.8 (±42.3)μm and was positively correlated ($r=0.877$, $p<0.001$) with increasing acid exposure time (Figure 1).

The average profile loss increased from 9.1 (±5.1) to 18.6 (±16.2) μm and as acid exposure increased, the average profile loss also increased with a positive correlation ($r=0.663$) and this was statistically significant ($p=0.019$). A strong correlation was observed between maximum profile loss and average profile loss over time ($r= 0.789$, $p =0.002$). See Figure 2. Acid Exposure Time vs Average Profile Loss

After the first 10-minute immersion volume change (mm^3) was -0.45mm^3 (±2.59) which increased to -1.31 (±3.78) mm^3. Large standard deviations were noted and a poor correlation ($r= 0.074$) with increasing acid exposure was observed. Differences at different time points were not statistically significant ($p=0.818$). There was no correlation between volume loss and average profile loss ($r= -0.143$). See Figure 3, Acid Exposure vs Volume Change.

4. Discussion

As acid exposure increased, both the maximum and average profile loss values increased and were detected by the intraoral scanner. These results suggest that the IOS has the capability of detecting early erosive wear when profile differences are measured. Thus, the null hypothesis was rejected. However, the standard deviations and the process error were too big to perform accurate volumetric analysis. This indicates that the process requires improvement and further

validation prior to routine clinical use. One potential benefit of clinical application might be that a larger surface area of enamel and dentine will be scanned (for example, a full arch). This may improve the sensitivity of the method to small changes in erosive tooth wear since they might be occurring over a large surface area. In our experiment, only a small area was measured necessitating a higher trueness and precision from the IOS.

A potential reason for the large standard deviations is the smoothing effect of interpolation of data points to form triangles during surface creation. The size of the average triangle created by the 3M True Definition IOS is 50 µm. This interpolates the data between measurements and limits accuracy, in all three dimensions, to 50 µm 'average patches'. Any further adjustments to the dataset, such as further smoothing or filling holes, which are available on many softwares to make the 3D mesh look more homogenous further increase the inaccuracy of the data. Another reason for the large standard deviations may be that natural enamel samples were used. These samples are less susceptible to acid challenge than their polished counterparts which are more commonly used in *in vitro* research [38]. Although the surfaces were standardised using only the buccal surfaces of molar teeth, the teeth were from different donors and different surfaces will have different rates of wear. This may have contributed to the high standard deviations.

In addition to the large standard deviations, measurements consistent with tissue gain were also observed despite physiological enamel regrowth being impossible. This artefact is due the software minimising the distance between the scans during the alignment process irrespective of the physiological process and is a common error with superimposition software. In order to achieve a more accurate alignment, it is important that areas which have undergone significant change are excluded from the alignment process to minimise tilting of the dataset [39]. It is

also important to include this error in the alignment process when assessing the accuracy of the system.

This is the first study to measure erosive tooth wear using an intraoral scanner after multiple acid exposures. The majority of attempts to measure wear on natural surfaces are done *in vivo*, taking impressions and scanning the teeth using profilometry. Adhesively bonded metal artefacts [40,41] on dental surfaces have been used as reference areas from which to measure change. More recently superimposition software has been used [17,32]. However profilometers are limited to specialised settings and are not practical for wear measurements in general practice. Multiple *in vitro* studies have used profilometry to detect erosive wear changes at a micron level on highly polished enamel surfaces. Protocols for measuring wear on flat samples have been optimised for profilometry over many years and are not optimised for IOS scanning. From pilot studies, the line angles developed during the taping protocols are not handled well by the IOS as one might expect. Repeating this experiment with flat samples would favour the profilometer and not be representative of what the IOS is capable of measuring. Few studies have investigated natural surfaces due to difficulty in obtaining a reference area from which to measure a traditional step height via ISO standards. The measurement metrics used to quantify clinical wear are often different to conventional methods of profile measurement in erosive tooth wear. In vitro, step height profilometric measurements between a reference area and the eroded area are calculated to determine loss. This can be a representative single point step height or multiple measurements of the same sample and averaged. 3D measurements can also be determined by analyzing the depth of the whole of the wear scar created experimentally [42]. This is different to the average profile loss observed when the whole surface is used clinically. When there is localized area of loss, this is averaged over the whole surface thus producing a seemingly lower value. However it is more reflective of the clinical scenario and

reference surface alignment alongside intraoral scanners can be used in any practice with an intraoral scanner to give an indication of wear measurements.

The limitations of this study need to be addressed. The main limitation is the lack of an established gold standard e.g. profilometry to compare with measurements obtained with the intraoral scanner. This was the initial aim of our experiment; however the Z range of a curved natural enamel surface was too large for our confocal profilometers and the reflectance of the natural enamel samples corrupted the scans obtained with triangulation laser profilometry. Validation of the trueness of sub-visual measurements obtained with the intraoral scanner will be the focus of future work. If there was a systematic (trueness) error, sequential data can still be valid if the precision is good and you are measuring changes over time (assuming a linear systematic error). We believe that the correlations observed between increasing acid exposure and increasing mean profilometric loss are interesting and show that there is potential for the intraoral scanner to detect wear at a micron level. The requirement to have multiple, longitudinal measurements of the same samples limited the sample size which contributed to the large standard deviations, particularly as there is a great deal of natural variation within natural enamel. Nonetheless, the low precision levels do suggest further development of the scanners and processing software is needed.

In vitro studies differ from the *in vivo* environment. One of the key differences is the presence of saliva which protects against erosion in the oral cavity [43,44]. This experiment was performed in the absence of saliva. Immersing the samples in natural saliva prior to acid immersion may affect image acquisition of the IOS and subsequent alignment by adding a salivary film to the enamel. Saliva has a complex role in erosive wear resistance and further work is needed before the results of this study can be translated to a clinical setting.

Furthermore, we used the acrylic surfaces surrounding the samples as the reference areas for alignment. Whilst unlikely in an erosive environment, the acrylic may have undergone change and influenced the alignment. In addition, finding reference surfaces which have not undergone any wear within a clinical setting remains a limitation of translating this work and is outside the scope of this investigation. Finally, attempts were made to limit operator error by standardising powder layer thickness and homogeneity, however it is possible that this may affect accuracy when measuring at the margins of what the system is capable of detecting. Further work is needed to optimise the alignment of dental surfaces. Comprehensive validation work is needed to determine the detection threshold of wear with the intraoral scanner *in vitro* before we can accurately start to quantify wear *in vivo*. Ideally, saliva should be incorporated into the experimental protocol and additional tooth surfaces to provide a more comprehensive and representative set of data.

The results of this study suggest that intraoral scanners have low precision when monitoring wear quantitatively and would suggest that wear is best quantified by profilometry on study models. However, qualitative detection of wear on intraoral scans without quantitative analysis has a higher sensitivity to changes than clinical indices alone or assessing study models at different epochs [4,45]. Intraoral scanners show promise as tools for the diagnosis of progression of erosive tooth wear but further development is still required.

5. Conclusion

Scan data from an intraoral scanner showed increasing profile loss change observed with increasing exposures to acid. However, the precision was low suggesting difficulty of the IOS at detecting very small changes. Volumetric analysis was also not possible at this stage with the IOS data. This study indicates potential of the IOS as a method of capturing data for

detecting and monitoring early erosive tooth wear. However, further work needs to be done to refine the alignment and measurement process and to investigate the minimal amount of wear which needs to occur in order to be accurately measured.

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Figure Legends

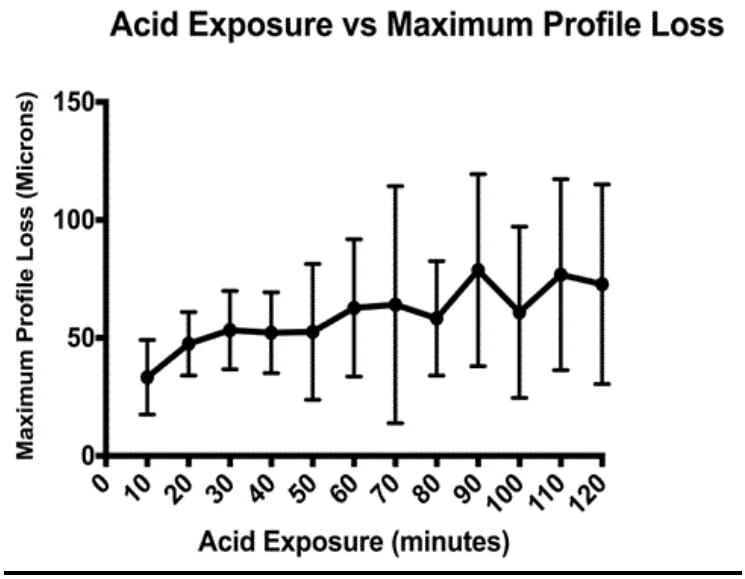

Figure 1 – Maximum profile loss (microns) after each 10-minute cycle of citric acid immersion

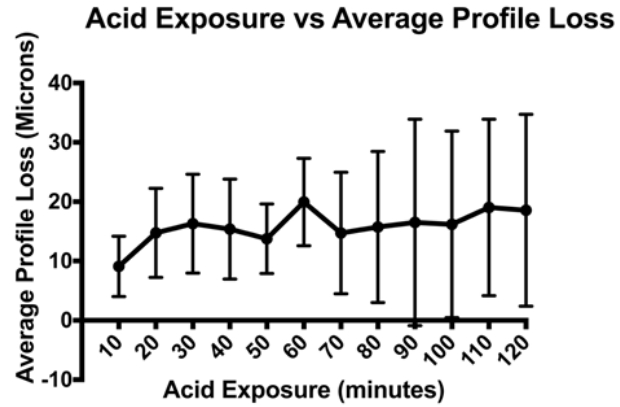

Figure 2 - Average profile loss (microns) after each 10-minute cycle of citric acid immersion

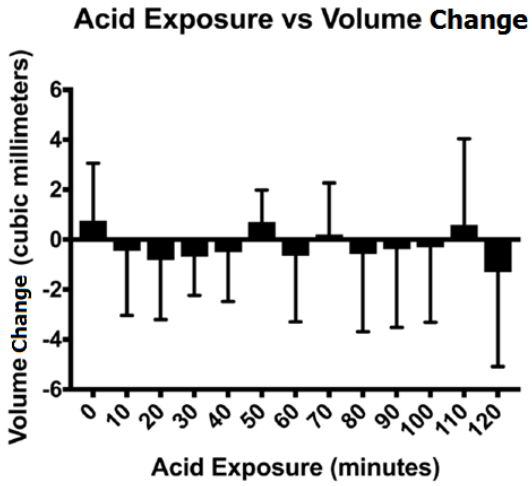

Figure 3 – Volume loss (mm^3) after each 10-minute cycle of citric acid immersion