Title: The influence of scanner precision on quantifying 3D intraoral changes

O'Toole S[1], Bartlett D[1], Keeling A[2,] McBride J[3], Bernabé E[4], Crins L[5], Loomans B[5]

Corresponding Author: Saoirse O'Toole
[1]Centre for Clinical, Oral and Translational Sciences
King's College London Faculty for Dental, Oral and Craniofacial Sciences,
Guy's Hospital,
London,
SE1 9RT, UK.
E-mail: Saoirse.otoole@kcl.ac.uk

[2]Department of Restorative Dentistry
School of Dentistry,
University of Leeds,
Leeds,
LS2 9LU, UK.

[3]Faculty of Engineering and the Environment,
University of Southampton,
Southampton
SO17 1BJ, U.K

[4]Division of Population and Patient Health,
King's College London Faculty for Dental, Oral and Craniofacial Sciences,
Denmark Hill Campus
London,
SE5 9RS, UK.

[5]Department of Dentistry,
Radboud University Medical Center,
Nijmegen,
6525 EX
Netherlands

Acknowledgements: This study was funded by the Academy of Medical Sciences (REF:

SGL020\1082). The authors declare no potential conflicts of interest with respect to the

authorship and/or publication of this article.

Total Word Count: 3,321

Key Words: Diagnostic systems, Digital imaging/radiology, Engineering, Imaging, Outcomes Research, Tooth wear

Abstract

Introduction: Three dimensional scans are increasingly used to quantify biological topographical changes and clinical health outcomes. Traditionally, this has been limited to specialised centres due to the necessity for expensive scanning equipment and complex analysis software. Within dentistry, improving technology has made cheaper, more accessible methods of data capture and analysis available, potentially facilitating a primary care system to quantify disease progression. However, this system has yet to be compared with previous high precision methods in university hospital settings. The aim of this study was to compare a dental primary care method of data capture (intraoral scanners) with a precision hospital-based method of data capture (laser profilometer) in addition to comparing open source and commercial softwares available to analyse data.

Methods: Longitudinal dental wear data from 30 patients were analysed using a two-factor factorial experimental design. At the same appointment, bimaxillary intraoral digital scans (TrueDefinition, 3M, UK) and conventional silicone impressions, poured in type 4 dental stone, were made at baseline and follow up appointments (36 months±10.9). Stone models were scanned using precision laser profilometry (Taicaan, Southampton UK). 3D changes in both forms of digital scans of the first molars (n=76) were quantitatively analysed in engineering software Geomagic Control (3DSystems, Germany) and freeware WearCompare (LeedsDigitalDentistry, UK). Volume change (mm^3) was the primary measurement outcome. The maximum point loss (μm) and the average profile loss (μm) were also recorded. Data, analysed in SPSSv25 (IBM, USA), were paired and skewed. Wilcoxon signed rank tests with Bonferroni correction were used.

Results: The median volume change (IQR) for Geomagic using profilometry was -0.37mm^3 (IQR-3.75,2.30) and for the intraoral scan +0.51mm^3 (IQR -2.17,4.26), $p<0.001$. In

WearCompare, the median volume change for profilometry was -1.21mm^3 (IQR -3.48,0.56) and -0.39 mm^3 (IQR -3.96,2.76) for intraoral scanning (p=0.039). WearCompare detected significantly greater volume loss than Geomagic regardless of scanner type. No differences were observed between groups when maximum point loss or average profile loss was analysed.

Discussion: As expected, the method of data capture, software used, and measurement metric all significantly influenced the measurement outcome. However, when appropriate analysis was used, the primary care system was able to quantify a degree of change and can be recommended depending on the accuracy needed to diagnose a condition. Lower resolution scanners may underestimate complex changes when measuring at a micron level.

Introduction

All clinicians should be able to quantify and assess whether a degenerative health condition is stable or progressing. This is possible in some diseases with biomarkers but is not always possible with soft and hard tissues. Measurement has typically taken the form of recording subjective visual changes and physical measurements of change are needed.

In dentistry, quantitative measurement of differences between sequential 3D scans of teeth have been used to diagnose erosive tooth wear. This is a condition where excessive acids from the diet and stomach can dissolve teeth. Due to changes in our diet and health, the prevalence is increasing, affecting 1 in every 3 adults globally [1]. Quantitative validation that tooth wear has progressed, potentially indicating the need for expensive restorations, has only been possible up until now in University Hospitals [2]–[5]. This has been achieved by scanning accurate moulds of the teeth with laser profilometers to create an accurate digital map of the surface with repeatable, calibrated point co-ordinates. As directly scanning teeth with lab-based profilometers is not been possible, scans of moulds of the teeth have been

aligned and compared, using custom built or commercial engineering software to quantify change. As data capture has typically been very accurate, small process errors have been calculated in the range of 15 microns [6], [7]. However, the reliance on research laboratory based scanners and engineering analysis software is complex, expensive and unfeasible for use in primary care [6]–[8].

Digital handheld scanners, known as intraoral scanners (IOS), take digital maps of the teeth and are increasingly used in primary care. They do not generate aerosols and are more amenable to effective cross-infection control compared to conventional impressions which generate aerosols and can harbour organisms [9]. This may increase their use in the current Covid-19 pandemic. IOS capture data via different methods from video capture to the use of confocal, triangulation or active wavefront principles. Rather than relying on accurate calibrated data point collection on an unmoving subject, multiple data points are captured and stitched together with company-specific algorithms. Errors are generated when the scanner fails to collect sufficient data to stitch a digital map of the surface (undersampling) [10], [11] or when the process fails, particularly with more than one tooth [12], [13]. Furthermore, data stitching algorithms often interpolate or smooth missing or erroneous data meaning that datapoints are estimated, non-uniform and lack adequate surface detail for changes to be measured at the micron level.

The softwares used by commercial companies to analyse digital maps rely on using an iterative closest point (ICP) algorithm to merge the maps to the closest possible alignment, without considering if the proposed alignment solution makes biological sense [14]. We have shown that this leads distortions and can result in physiologically impossible outcomes [15], [16]. We have recently incorporated feature recognising elements [16], [17] into an ICP algorithm to minimise these errors and created an open-source freeware to be used alongside

any 3D scan. Although it has been validated against previous gold standard software [18], it has not been tested on longitudinal clinical data to date.

The combination of a data collection from primary care and free, user-friendly software for analysis may create new opportunities for monitoring disease. However, the accuracy of measuring change in scans will be influenced by the scanner, software and the interaction between them. This paper uses a factorial design to compare data obtained from profilometric scans of casts and that obtained from direct intra oral scans using two registration softwares; a commercial software (Geomagic Control, 3Dsystems, Germany) or a freeware (WearCompare, Leedsdigitaldentistry, UK). We expect there to be differences in the measurements obtained between the scanners but we do not know whether this difference will be clinically significant. The primary null hypothesis proposes that the dental wear data, specifically the volume change, average profile loss and maximum point loss, detected by the profilometer will not be different to wear data obtained with the intraoral scanner. The secondary null hypothesis is that the software used to analyse the data will not influence the volume change, average profile loss and maximum point loss observed for either scanner.

Methods

Data was collected from a larger clinical longitudinal erosive tooth wear study (Radboud Tooth Wear Project ABR code: NL31371.091.10) [19], [20]. Study participants had been referred by general dental practitioners to the Department of Dentistry of the Radboud University Medical Center (Nijmegen, The Netherlands) for management of erosive tooth wear. Those in the monitoring arm who provided additional written consent for their data to be transported to the UK (ABR codes NL31401.091.10) and additional analysis performed were included in the study (n=25, age 35.8 ± 6.8 y, 20 male, 5 female) . A power calculation was performed in GPower vs 3.1 [21], using a two tailed test, estimating a correlation of 0.4 between the scanners at 95% power with $p<0.05$, estimated that a sample size of 75 was

required. The data transported to the UK included digital intraoral scans using Lava Chairside Oral Scanner (3M, USA) at baseline and 3M True Definition Intraoral Scanner (3M, UK) at follow up and analogue dental impressions taken with addition silicone (Ivoclar Virtual 380, Ivoclar Vivodent, Liechtenstein, Europe). Impressions had been poured in type 3 dental stone (SLR Dental GmbH, Germany) within 24 hours of impression taking according to the manufacturer's instructions.

Both the digital and dental impressions were captured by the same trained operator. The point clouds of recognised index teeth (the occlusal surface of the first molars [22], [23]), were isolated by the operator (SOT) and set aside for evaluation. From each analogue study model (n=100) were scanned using a non-contact triangulation laser profilometer (XYRIS 2000TL, Taicaan Technologies, Southampton UK) in a raster pattern using a step-over of 50 µm with a repeatability error of 2.6 µm [24]. This generated a 3D point cloud data set for comparison.

Quantitative analysis of change between sequential scans from the profilometer and intra-oral scanner was performed in both Geomagic Control 2011 (Geomagic, Morrisville, North Carolina, USA) and WearCompare (Leeds Digital Dentistry, Leeds, UK). Data points, selected by the operator, on the buccal and lingual surfaces were chosen as reference areas and used for analysis using previously published protocols [16]. For Geomagic, a best fit alignment of 1000 data points on reference surfaces, followed by a refined alignment using 5,000 data points was performed. For the reference alignment, the occlusal surface was deleted from the dataset leaving the buccal and lingual reference surfaces. A best-fit alignment process using 1,000 data points from the reduced dataset was performed, followed by a more refined alignment of 5,000 datapoints. The transformation matrix was then applied to the complete displaced dataset to realign it with the same orientation. For WearCompare, an initial global alignment utilising a feature-based recognition system was performed. The same buccal and lingual reference surfaces were selected for refined ICP alignments which

highlights corresponding reference areas within 25 microns of each other. The occlusal surface was selected to be measured and all measurements were taken perpendicular to the occlusal surface.

Volume change (mm^3), maximum point loss (μm) and the mean loss over the surface (μm) were analysed for each surface for both scanners and softwares. For a secondary volumetric analysis any positive values, indicating either gain or error, were set at zero.

This study utilised a two-factor factorial experimental design comparing two different methods of data capture (profilometer and intraoral scanner) and two different analysis softwares with different alignment principles (Geomagic Control and WearCompare). Descriptives of all measurement metrics were calculated and normality assessed using Shapiro Wilks test and histogram assessment. Data were paired and skewed. Wilcoxon signed rank tests were used to compare outcomes (volume change (mm^3), maximum point loss (μm) and the average loss over the surface (μm)) between groups. Bonferroni correction was applied to compensate for multiple comparisons. The significance level was set at (0.05/6=) 0.008 to identify differences between groups. Single measures Intra-Class Correlations (ICC's) were performed between data capture method (scanner) and data analysis method (software). All analysis was performed in SPSS vers 25 (IBM Corporations, Armonck, USA). Statistical significance was inferred at $p<0.008$

Results

From the original data collected in the Netherlands, 76 surfaces were analysed representing an average follow-up time of 36±10.9 months. Initially data was analysed using previous gold standard commercial software Geomagic. Laboratory profilometry data analysed in Geomagic showed a median volume loss of -0.37 mm^3 (IQR-3.75, 2.30) but a median volume gain for the intraoral scan data of +0.51 mm^3 (IQR -2.17, 4.26) and this was statistically different ($p<0.001$). The median profile loss for the laboratory profilometer was 55.8 μm

(IQR 24.43, 77.60) and 43.65 μm (IQR 29.93, 77.95) for the intraoral scan (p=0.001). The maximum point loss on the occlusal surface for the profilometer was 398.4 μm (IQR 238.7, 533.7) and 303.9 μm (IQR 217.6, 483.0) for the intraoral scan (p=0.01).

Data from freeware WearCompare, showed a median volume change for the profilometer scan was 1.21 mm^3 (IQR -3.48, 0.56) and -0.39 mm^3 (IQR -3.96, 2.76) for the intraoral scan (p=0.039). The median profile loss for the profilometer scans was 44.8 μm (29.48, 91.63) and 43.10 μm (IQR 24.43, 77.60) for the intraoral scans (p>0.05). The median maximum point loss on the occlusal surface for the profilometer scan was 317.1 μm and 278.3 μm (IQR 170.8, 494.0) (p<0.05). No statistical differences were observed between the profilometer scans and intraoral scans when measurements were analysed in Wear Compare.

Table 1 reports the measurement metrics for each scanner and software. WearCompare detected significantly greater volume loss than analysis in Geomagic regardless of the scanner type.

Table 1. Measurements obtained from analysing wear progression over 3 years by scanner and software.

	Laser Profilometer	**Intraoral Scanner**	
	Median (IQR)	Median (IQR)	Difference between scanners
Geomagic			
Volume Change (mm^3)	-0.37 (-3.75,2.30)	0.51 (-2.17,4.26)	p<0.001
Average Profile Loss (μm)	55.80 (24.43,77.60)	43.65 (29.93,77.95)	p=0.001
Maximum Point Loss (μm)	398.4 (238.7,533.7)	303.9 (217.6,483.0)	p=0.010
WearCompare			
Volume Change (mm^3)	-1.21 (-3.48, 0.56)	-0.39 (-3.96,2.76)	p=0.037
Average Profile Loss (μm)	44.80 (29.48,91.63)	43.10 (24.43,77.60)	p=0.182
Maximum Point Loss (μm)	317.1 (198.0,466.4)	278.3 (170.8,494.0)	p=0.770

Difference between softwares	
Volume Change (mm^3)	p<0.001
Average Profile Loss (μm)	p=0.277
Maximum Point Loss (μm)	p=0.255

Table 2 reports the volume changes when positive values were set at zero. The median volume change for the profilometer was unchanged but for the IOS volume loss was 0.00mm^3 (IQR -2.17, 0.00). A statistical difference was observed between profilometry and IOS data for Geomagic analysis (p=0.016) but no difference for WearCompare analysis.

Moderate intra class correlations (ICC's) were observed analysing volume change data between the scanners and softwares.; 0.476 (p<0.001) for Geomagic and 0.457 for WearCompare, p<0.001. WearCompare and Geomagic data had slightly higher intraclass correlation of 0.673 (p<0.001) when the intraoral scanner data was analysed. Table 3 reports single measures intraclass correlations (ICCs) between the scanners and softwares for volume change.

Table 2. Volume changes observed over 3 years when positive data is set at zero. A commonly used method by many commercial companies.

	Laser Profilometer	**Intraoral Scanner**	**Difference between scanners**
	Median (IQR)	Median (IQR)	
Geomagic			
Volume Change (mm^3)	-0.37 (-3.75,0)	0.00 (-2.17,0)	p=0.016
WearCompare			
Volume Change (mm^3)	-1.21 (-3.48,0)	-0.39 (-3.95,0)	p=0.361
Difference between softwares for each scanner type	p=0.289	p=0.091	

*Statistically significant after Bonferroni correction for multiple comparisons applied

Table 3. Single measures intraclass correlations (ICCs) between the scanners and softwares for volume change.

	Correlations between Laser Profilometer and Intraoral Scanner		
	ICC	95% CI	p value
Geomagic	0.476	(0.281-0.632)	p<0.001
WearCompare	0.457	(0.259-0.618)	p<0.001
	Correlations between Geomagic and WearCompare		
	ICC	95% CI	p value
Intraoral Scanner	0.673	(0.529-0.780)	p<0.001
Laser Profilometer	0.525	(0.341-0.671)	p<0.001

Discussion

This paper demonstrates the differences in outcomes which can be observed between low resolution primary care digital scanners and precision measurements from hospital laboratory profilometers when attempting to measure biological changes at a micron level. As expected, increased volume change values were observed using the higher resolution and calibrated profilometer scans compared to the intraoral scans. Unexpectantly, this was only statistically significant when commercial softwares, previously thought to be the gold standard, were used for the analysis. The custom built freeware outperformed the commercial software. The null hypothesis was therefore partially rejected. This finding suggests that if the analysis is conducted accurately, it may compensate for the decreased resolution of the scanner. This is a promising finding and has implications for the development of primary care systems.

There are several possible reasons for the reduced volume changes observed in intraoral scanners. Data interpolation or the mathematical averaging of datapoints across a surface can smoothen the topography of the surface and may overlook small discrepancies/areas of change in the surface. Smooth surface lesions, potentially on the buccal and lingual reference

areas, will be subjected to heavy data down sampling internally in the scanner as the topography is not deemed as important. Smoothened surfaces are more susceptible to inaccuracies in data registration and alignment [15] as it will increase the mathematical tendency to minimise differences towards any sloped surfaces (in this case the occlusal surface). This can result in inaccuracies in alignment and biologically implausible outcomes. Analysis in a software which ignores features or the holistic geometric shape, such as Geomagic in this study, will be particularly susceptible to this. Combining Geomagic analysis with the intraoral scan data resulted in an overall volumetric tooth tissue gain, which is physiologically impossible, indicating large errors within the analysis process.

For WearCompare, errors did not occur to the same extent resulting in overall negative values for wear progression for both the profilometry and IOS scans. Recent techniques developed in Radboud university involve using reference areas for alignment on the occlusal surfaces in addition to the buccal and lingual surfaces providing additional control of the alignment in the Z axis. This may facilitate less translation and angular error and less positive values. However, this increases the analysis time and may underestimate wear if an ICP algorithm is used in the Z axis. Further research will focus on validating this technique.

The correlation between wear measurements taken with the scanners was moderate as there are inherent but different errors for each form of data capture. Undetected, sub-visual errors on casts or scans may have been present and subsequently analysed as wear data. The profilometer is unable to scan undercuts which meant that less surface area can be used for selective surface alignment. In contrast, the IOS was successful at scanning undercuts. However, missing data or incomplete intraoral scans can also create errors whereby triangle

size is distorted and measurements can be skewed [25]. Recognising where errors may lie in each scan type will facilitate more accurate analysis.

Differences were observed between the profilometer and IOS data when positive values were omitted in this study. Discounting positive values, commonly done in many commercial softwares and when profile loss and maximum point loss measurement metrics are reported, do not show error within the system. We observed that this can cause clinically significant changes to the outcome. Colour maps of aligned scans can visually indicate areas of change but the quantification does not always reflect the severity. Discounting positive data increases the likelihood that a poor alignment will not be detected and wear underestimation or overestimation can occur. Reporting the negative changes only may be useful when trying to communicate wear to patients, but these metrics have limited diagnostic potential when measuring successive rates of wear.

This paper has several limitations. Analysis was performed blinded to the sequence of scanning to limit bias. However, there were often indications of sequence such as surface restorations or clear visual wear progression in the interim period. Although one make of intraoral scanner was used, the hardware and software changed over the 3 year period, of the study, emphasising that research in this fast-moving field becomes rapidly out-dated. Other intraoral scanners will have slightly different methods of processing missing data and interpolating irregularities and it is possible that slightly different results may be achieved with different intraoral scanners. Single tooth analysis was performed to maximise accuracy which limits generalisability to full arch analysis. A large limitation in longitudinal wear analysis is the true wear progression is unknown. One has to assume that wear has occurred and positive values are errors in alignment or in the data capture process. This makes it is difficult to identify any form of measurement as a gold standard.

Conclusion

This study shows that low resolution scanners can be used for measurements at micron level provided appropriate analysis techniques and software is used. This could represent a step change in the way that erosive tooth wear is diagnosed and treated. From a dental point of view, the ability to view digital scans with increased magnification on a monitor also offers an increased diagnostic advantage. However, there is a duty of care on the profession and research community to not overestimate the quantitative capabilities of digital scanners to inform treatment or care outcomes until we are certain that they are adequately sensitive and specific to do so. This will depend on the level of accuracy required from the analysis process to diagnose disease progression within a feasible diagnostic window. The resolution and accuracy of primary care scanning tools is likely to increase rapidly and further work should concentrate on reducing the process errors inherent within each measurement system.

Acknowledgements: This study was funded by the Academy of Medical Sciences (REF: SGL020\1082). The authors declare no potential conflicts of interest with respect to the authorship and/or publication of this article.

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