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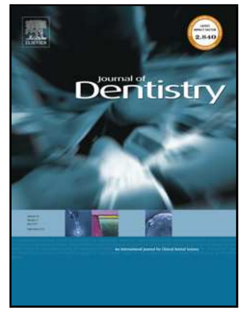

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Title: Confounding Factors Affecting the Marginal Quality of an Intra-Oral Scan

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Abstract

Title: Confounding Factors Affecting the Marginal Quality of an Intra-Oral Scan

Objectives: To assess the effect of clinical factors on the quality of intra-oral scans of crown margins. These factors are; presence of adjacent teeth, proximity to gingivae, encumbrance of wand positioning within oral cavity.

Methods: A typodont lower molar (Frasaco, Germany) was prepared for an all-ceramic crown with 1.5mm supraginigival (lingual) and equigingival (buccal) margins. The tooth was scanned in a model scanner, creating a master scan.

An intra-oral scanner (IOS) (Omnicam, Sirona Dental) was used to acquire sets of 5 scans each, under varying conditions; 1)the presence/absence of adjacent teeth, 2)model mounted in manikin head/hand-held, 3)with/without a 1mm shim to elevate the margin. Every combination was investigated, yielding 40 scans (8 groups of 5).

The master scan margin was identified by selecting the highest curvature region (>1.8). The master was aligned to each IOS scan, and 4 regions of each IOS scan margin were extracted, lying within 100µm of predefined mesial, distal, buccal and lingual sections of the master margin.

The mean curvature of each margin section was calculated using Meshlab. The effect of each confounding factor on margin curvature was analysed using ANOVA.

Results: Lingual margin curvature remained consistent regardless of scanning conditions. Buccal margin curvature was significantly affected when located equigingivally. Mesial margin curvature was significantly affected in the presence of adjacent teeth and proximity to the gingivae. Distal margin curvature was significantly affected by all three confounding factors.

Conclusions: The curvature (sharpness) of the margin recorded by a commercial IOS is significantly affected by clinical factors obscuring visibility.

Keywords: Prosthodontics, scanning, intraoral, CAD/CAM, impression, margin

Introduction

A good impression for a fixed dental prosthesis should capture, among other things, the full margin of the preparation along with some unprepared tooth below the margin [1]. This ensures the technician can clearly identify the finishing margin and produce an appropriate emergence profile.

The quality of marginal fit is likely to be an important factor affecting the longevity of indirect restorations [2]. The susceptibility to leakage from a poorly fitting margin can lead to secondary caries or pulpal effects. The best measure by which marginal fit can be judged is not clear. Many workers use cross sections of replicas to quantify mean marginal gaps in 2-dimensions, generally providing up to 8 samples around the circumference of the tooth [3,4]. However, the maximum marginal gap has been suggested as the most clinically relevant measure [5], since this would likely form the point of failure of the marginal seal. The acceptable size of a marginal gap is also not clear, although values in the region of 100μm have been suggested for conventional cements [6].

Since its inception over 30 years ago, intraoral scanning has become an increasingly popular method for recording impressions for dental prosthodontic treatment [7]. Much work has been reported comparing the trueness and precision of these scans to traditional impressions. In some cases comparisons are made between impressions of unprepared full dental arches [8–10]. In other works, the reproduction of individual crown preparations is assessed [3,4,11]. Modern intraoral scanners (IOSs) have a level of accuracy and precision comparable to, but not quite as good as, traditional techniques when recording full dental arches *in vivo* or *in vitro* [8–10]. In contrast, much of the work on individual crown preparations reports that IOSs produce crowns that are at least as accurate as those from scanned models of traditional physical impressions [12,13]. Much of this work is undertaken *in vitro* under ideal scanning conditions. Flugge [14] has shown that there is a deterioration in scan quality when using IOS's *in vivo*.

Whilst it seems true that IOSs are capable of recording accurate impressions of crown preparations under ideal conditions, the effect of common confounding factors on the quality of the digital impression has not been investigated.

In essence all IOS's require a direct line-of-sight on to any area they wish to record. If the local anatomy or morphology will not allow this, the area will not be recorded. Limitations to the line-of-sight may come from local anatomy (for example equigingival margins or adjacent teeth obscuring the view), or from more general confinements such as limited scanning wand positioning in the oral cavity. Less obviously, even if a line-of-sight is available, the quality of the scan may be affected by factors such as distance, angle of incidence and the arc of available viewing angles (the latter being the result of the 'quality assignment' that optical scanners apply to each scanned vertex, and the subsequent weighted averaging of all vertices within a small region). Therefore, assuming a region was visible from a restricted viewing angle, the operator will see that the scanner has captured the region and might assume that this area has been satisfactorily scanned. In reality, the quality of the scan in this region might be inferior due to the limited arc of visibility, or unfavourable wand orientation. Poor wand positioning is a major reason why IOS's have been shown to be technique sensitive [15]. Furthermore, limitations in wand positioning imposed by the structure and size of the oral cavity, the position and morphology of the tooth/preparation, and proximity to adjacent teeth may mean that it is sometimes not possible to achieve a line-of-sight to all areas of importance, despite the best clinical technique.

One metric by which the margin quality could be assessed is the 'curvature' of the margin. In computer graphics, each point in a 3D mesh is orientated (ie it is facing in a certain direction). The direction of orientation is called the 'normal', and the divergence of a points' normal, compared to its neighbours, is used to give a value of curvature at that point on the surface. High curvature values imply sharp edges whilst a curvature of zero means the surface is completely flat. Negative curvature values occur in concavities. Curvature is defined as the reciprocal of the radius of a sphere aligned to that 'patch' on a surface. Therefore, by definition a sphere with a radius of one has a curvature equal to one.

The curvature is used in many dental CAD packages to help locate the margin semi-automatically. Areas of lower curvature will require the user to make a guess as to where the margin should lie, adding imprecision to the procedure. These 'low curvature' regions can occur in areas where the scan quality is poor, or where the software has to interpolate and smooth the data (Figure 1).

The aim of this study was to investigate the factors which may affect the curvature of the margin recorded in an intraoral scan of a lower left first molar. The factors investigated were:

1. The presence or absence of adjacent teeth
2. The position of the margin relative to the gingivae
3. The positional wand limitations imposed by the simulated oral cavity

The effects of these confounding factors were investigated separately for margins located mesially, distally, lingually and buccally. The null hypothesis was that the marginal curvature of a single typodont all-ceramic preparation (36) will be the same, regardless of the confounding factors outlined above.

Materials and Methods

A typodont lower left first molar (Model AG-3, Frasaco GmbH, Tettnang, Germany) was prepared for an all-ceramic eMax (lithium disilicate) crown, with a 1mm shoulder margin, 2mm occlusal reduction and an 8 degree taper. The lingual margin was positioned 1.5mm supragingivally to act as a control throughout the experiment. The buccal margin was positioned equigingivally, while the approximal margins lay within 0.5mm of the gingivae, moving more supragingivally as they went from buccal to lingual. The unprepared tooth below the mesial margin had a mesio-angular emergence profile whilst the tooth surface below the distal margin was relatively vertical (Figure 2).

The single molar was scanned in a dental model scanner (Rexcan DS2, Europac 3D, Crewe, UK) which has a trueness and precision of <10µm. The STL file was imported into Meshlab (http://meshlab.sourceforge.net/) and the pseudo inverse quadric curvature filter was applied using the default settings, to calculate the curvature at all vertices on the mesh. Next, the margin was selected by choosing all vertices with a curvature greater than 1.8 (Figure 2). The margin was then further subdivided manually into four regions representing the mesial, distal, buccal and lingual zones (Figure 2). These four margin sections were saved for use as the master templates.

The prepared tooth was placed in a Frasaco jaw model. Throughout the following experiments, a single experienced operator performed all the scans. In each case, a scan was made then reviewed in the software for holes, then every effort was made to rescan areas of poor quality. A single IOS (CEREC Omnicam, Sirona Dental, USA) was used throughout, following calibration as per the manufacturer guidelines. The scans performed were:

a) 5 scans whilst holding the model by hand (allowing optimal viewing angles for the scanning wand), with all adjacent teeth *in situ*.

b) 5 scans with the model mounted in a manikin head, with the opposing upper model also in position and all adjacent teeth *in situ*.

c) 5 scans whilst holding the model by hand, with teeth 37, 34 and 35 removed to allow better access for the scanning wand.

d) 5 scans with the model in a manikin head, with teeth 37, 34 and 35 removed.

Next, the prepared tooth (36) was removed from the model and ten 0.1mm metal shims were inserted in the socket. The tooth was replaced and screwed firm, causing it to sit 1mm higher above the gingivae. The scanning protocol outlined above was repeated. Thus a total of 40 scans were taken, in groups of five, with each group representing a different combination of confounding factors; restricted range of movement in the oral cavity, presence of adjacent teeth and proximity of margin to the gingivae.

All scans were exported as STL files and the preparations were each aligned to the master preparation scan. Each mesh was subdivided to create a uniform triangle mesh with a mean edge length of between 15 and 17 microns. This process did not alter the topology, but ensured that all subsequent measurements would be evenly sampled. The curvature at each vertex was then calculated as before.

Next the margin sections (mesial, distal, buccal and lingual) were extracted from each scan by overlaying the master preparation margin sections and selecting all points on the test scan that lay within 100µm of the master margin section. The mean curvature for each margin section was recorded. This method enabled precise identification of the correct margin, even in areas where scanning artefacts and smoothing precluded clear margin visibility (Figure 3).

In a final step, the overall means for each group of 5 scans were calculated, and the results plotted as bar charts to compare the effect of different confounding factors on the mean curvature of each margin section.

The normality of the each group was assessed with the Kolmogorov-Smirnov (KS) test. If the data were normally distributed, the effect of each combination of confounding factors was assessed for statistical significance ($p<0.05$) using univariate ANOVA with fixed factors and their interactions, and Bonferroni correction was used to adjust for multiple pairwise comparisons (IBM SPSS Version 22.0). If the data were not normally distributed, a non-parametric method such as Kruskal-Wallis test would be used to compare the effect of each combination of confounding factors.

Results

The mean curvature values over the five scans, for each permutation of confounding factors are shown in Table 1 to Table 4, and are plotted for each margin section in Figure 4 to Figure 7. The data for each group was normally distributed according to the KS test, thus univariate ANOVA was applied to each margin section to assess the effect of confounding factors. Statistical analysis revealed the following (the detailed between-subjects ANOVA analyses for each margin section are presented in supplement tables A to D):

- The main effects of any factors were not statistically significant for curvature of the lingual margin.
- The buccal margin curvature differed significantly when recorded in the +1mm elevated position ($p<0.001$). No other factors significantly affected the recorded curvature.
- The presence of adjacent teeth was a significant factor affecting the curvature of the mesial margin ($p<0.001$). Elevating the margin by 1mm also had a significant effect on the recorded curvature ($p=0.008$).
- All three confounding factors had a significant effect on the recorded curvature of the distal margin ($p<0.001$ in all cases).

An example scan (intra-oral, adjacent teeth present, 1mm shim *in situ*) is shown in Figure 8. Distortions of the margin are clearly visible, causing 'bulging' distally and an artificial 'bridge' mesially, which merges with the adjacent premolar. All scans with adjacent teeth present showed some degree of bulging or bridging of the mesial and distal margins. Only when the tooth was lone-standing, elevated on the 1mm shim, and scanned extra-orally was it possible to consistently capture a margin with no visible distortions.

Discussion

The use of margin curvature as a metric for quantitative analysis of impression quality at the margin is presented. This is a clinically relevant measure since it relates to the definition of the margin and will have implications on the quality of prosthodontic fit.

Our method uses a scan of the prepared tooth in a model scanner to define the gold-standard margin location. Following this, the margins on all test scans are defined by their proximity to this gold-standard. This is necessary because some areas of the test scans showed zero curvature, making independent identification of the margin on each test scan impossible. It is important to note that in this context, 'gold-standard' does not necessarily mean a perfectly sharp margin was captured by the model scanner, but rather, the *location* of the margin was precisely identified (to within the manufacturer quoted trueness and precision of 10µm).

The absolute value of curvature is not important, because our definition of a margin will always include 'flat' areas within 100 microns of the edge. The mean curvature includes these flat areas, and for this reason a uniformly dense mesh is required to ensure regular data sampling. This means that while the absolute curvature of a test segment of margin is not important, the relative values of that same segment, scanned under different confounding factors, are valid.

Not all possible confounding factors were investigated. *In vivo* hindrances such as moisture, muscular soft tissues, and/or limited jaw opening are likely to further decrease the efficacy of the scan. Furthermore, only one tooth location (lower left first molar) was investigated here. Wand positioning may be further hindered with scans of second and third molars. Despite these limitations this work helps to identify which clinical factors should be considered when choosing an appropriate impression technique.

The lingual margin served as a control because it was supragingival in all scans (1.5mm supragingival or 2.5mm supragingival, depending upon the conditions). Furthermore, the margin was clearly visible to the scanning head, regardless of whether the model was mounted in the manikin head or not. The presence of neighbouring teeth did not affect this visibility. There were no significant confounding factors affecting the curvature of the lingual margin. Therefore, in the absence of any significant encumbrance to the line-of-sight, the IOS produced scans of consistent marginal quality.

The buccal margin was also relatively accessible to the scanning wand, regardless of whether the model was mounted in the manikin head or not. However, the groups of scans that had the buccal margin positioned equigingivally showed a significant difference in the recorded curvature compared to the scans where the margin was 1mm supragingival. This could be attributed to the inability of the scanner to 'see' down the gingival crevice, instead using 'hole-filling' to join the margin horizontally to the crest of the gingivae. This in turn decreases the sharpness and definition of the margin. In the presence of one confounding factor – equigingival margins – the buccal margin curvature was significantly different compared to clearly visible supragingival margins.

A significant confounding factor for the mesial margin was the presence of adjacent teeth. Margin sharpness was lower for all scans taken with adjacent teeth *in situ*, compared to all the scans taken with a lone standing tooth. This is probably due to obscured areas for which it was impossible to achieve a reasonable number of viewing angles. Factors such as marginal proximity to adjacent teeth, height of adjacent teeth, emergence profile of the unprepared tooth under the margin, and the contour and inclination of teeth will all affect the ability of the scanner to directly view all aspects of the dentition. In these circumstances, the scanner must fill the gaps or acquire inferior data, and this often led to artificial bulges on the margin, or even 'bridges' between the preparation and the adjacent tooth. This will likely lead to an inaccurate marginal fit in this area, and this is unfortunate because it is these 'difficult to clean' areas that demand a good marginal seal.

The mesial margin curvature was also significantly affected by proximity to the gingivae, with 1mm supragingival margins being recorded with a higher mean curvature. Scanning in the manikin head did not affect the result indicating that all necessary viewing angles could be achieved *in situ* for the mesial margin of the lower left first molar. The presence of adjacent teeth significantly affected the recorded mesial marginal curvature of the mesial margin. The proximity of the mesial margin to the gingivae also had a significant effect on curvature.

The sharpness with which the distal margin was recorded was significantly affected by all confounding factors under investigation. The mean curvature, when scanned under ideal conditions (extra-oral, elevated margin, lone-standing tooth), was higher than for any of the other scanning conditions. Scans encumbered by the manikin head were adversely affected in the 'distal' group. This may relate to the limited angles of view with which it is possible to orientate the scanning wand when recording the distal margin of lower posterior teeth.

Significant crossover interactions were found in three cases as shown in supplement tables A, B and D, but the crossover effect may be underpowered due to the small sample size. Overall, the tested null hypothesis, that the marginal curvature of a single typodont all-ceramic preparation (36) will be the same, regardless of the confounding factors outlined above, must be rejected.

Whilst this study reveals the contributions of various clinical factors which may decrease the quality of margins scanned with an IOS, the clinical implications of these effects are less well defined. One might argue that if a traditional stone model were poured and the resulting margins had the appearance of 'bridges' or 'bulges' (Figure 8), it would be rejected and a new impression requested. However, digital scans are not directly comparable to stone dies. For example, a colour scan may help guide the identification of the margin, even if it lies on a flat or rounded bulge. Despite this, the inaccuracy of the margin at this position can be considerably more than 100µm (as shown in the cross sections in Figure 8) which may lead to a clinically unacceptable marginal fit.

This is in contrast with some of the literature, which finds marginal fit of IOS derived crowns to be good. However, many of these studies are missing one or more of the confounding factors outlined here. For example, some scan isolated preparations *in vitro* [16–20], while others have used a methodology which only samples a few discrete points around the margin [3,4]. It might be considered unlikely that such samples happen to occur through the poorest area of the margin, and many of the samples will be taken from 'good' parts of the margin, in turn weighting the result. For example, in the aforementioned works, three bucco-lingual sections were taken, whilst only one mesio-distal section was used. Furthermore, any poorly defined margins were excluded from Reich's study.

From a clinical standpoint, it could be argued that the poorest region of marginal fit is the area of greatest interest, rather than the mean fit from a set of uniform samples. It is this poor (and possibly inaccessible) region that might be expected to cause eventual clinical failure. Methods for quantifying the quality of scanned margins should identify the poorest region rather than the mean value.

This study is limited to the use of one IOS, and the results may vary with other scanners. However, given that all require a line-of-sight, and most have wands of comparable dimensions, it seems likely that the general pattern of the effect of confounding factors could be extrapolated to all intra-oral scanning systems.

In summary, when scanning a lower first molar typodont preparation using a commercially available IOS, the curvature (sharpness) of the margin is significantly affected by the presence of adjacent teeth, the proximity to the gingivae and the restrictions in wand positioning incurred by the (simulated) oral anatomy. All these factors affect the visibility of the margin and its surrounding hard and soft tissue. Approximal margins are particularly susceptible to these occlusions when adjacent teeth are present. Whilst we have shown that different scanning conditions affect the quality of the data that is recorded, more work is required to determine the clinical impact of these factors. In the meantime, clinicians should be mindful of these factors, and may wish to consider traditional impressions in some clinical situations where the anatomy precludes robust and complete optical scanning.

Conclusion

The curvature (sharpness) of the margin recorded by a commercially available IOS is significantly and detrimentally affected by factors obscuring the visibility of the surrounding tooth tissue. In particular the presence of adjacent teeth can obscure the view of approximal margins, leading to less sharply defined scans in these areas.

Clinical Significance

Intra-oral scanners require a direct line-of-sight when scanning crown margins. Common clinical factors (such as the presence of adjacent teeth, or encumbered wand positioning in the mouth) may prevent optimal scanning, causing inferior impressions. Clinicians should choose an appropriate impression technique (optical or traditional) based on assessment of these factors.

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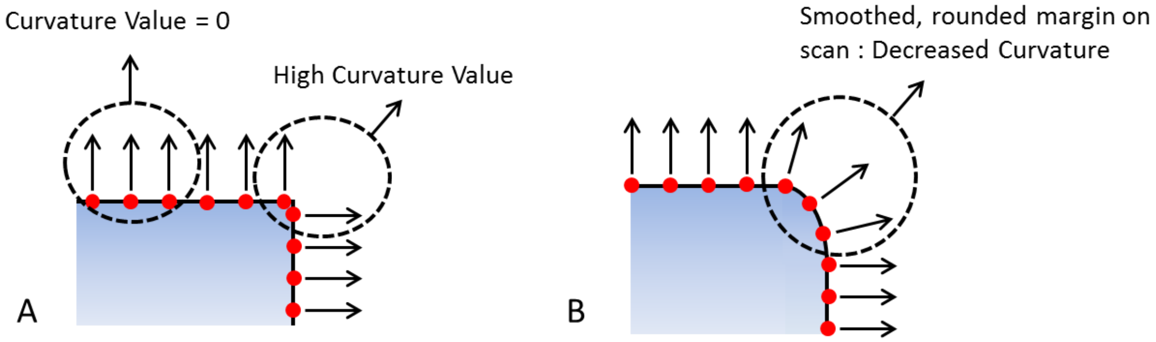

Figure 1 The Curvature of a Margin. A good scan of a well-defined shoulder margin is shown (A). The 3D points (red) are orientated in the direction of the underlying surface (black arrows). Flat regions have zero curvature because the angle between adjacent points is zero. The sharp shoulder margin has a high curvature because the angle between adjacent points is high. A poor scan of the same shoulder is shown in (B). Here, the software has 'smoothed' the shoulder due to missing data in the scan. The value of the curvature at the margin will be decreased, and this serves as a measure of the quality of the scan at the margin.

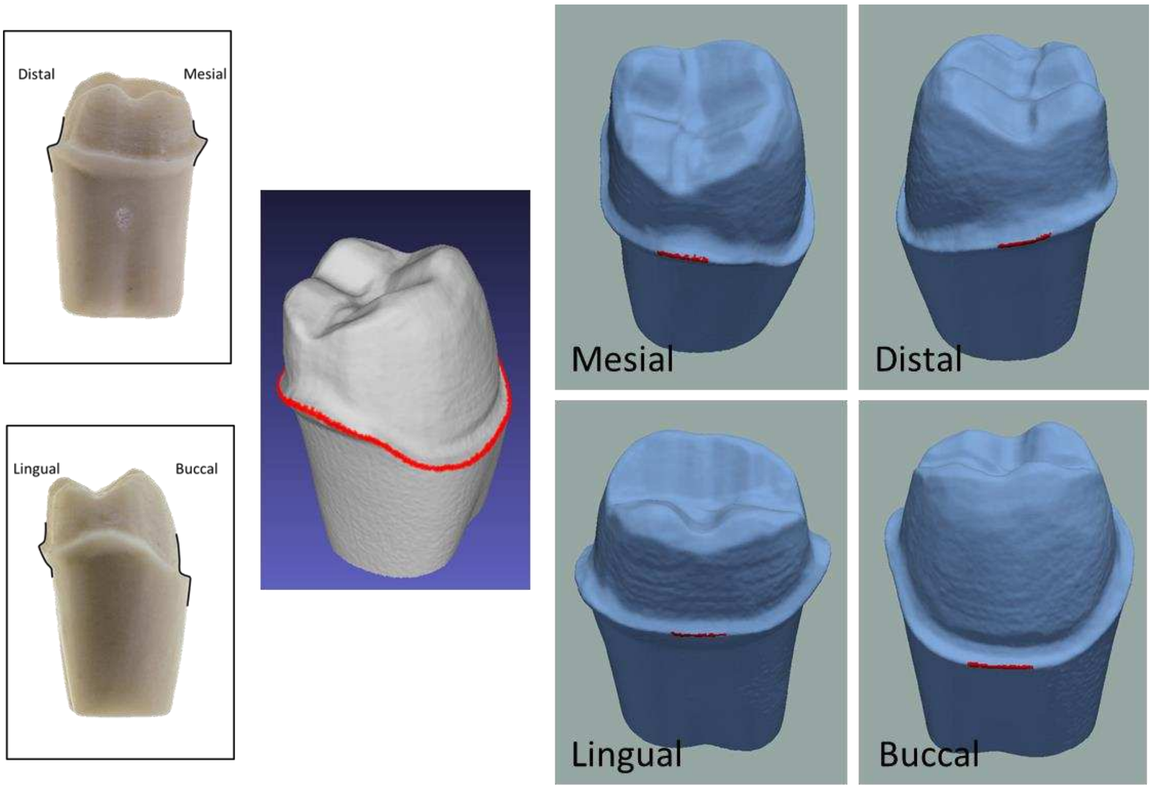

Figure 2 The All-Ceramic Preparation and Margin Selection. Left: The prepared master had well defined margins. The buccal margin lay equigingivally whilst the lingual margin was 1.5mm supra-gingival. The unprepared tooth below the mesial margin had a mesio-angular emergence profile. Middle: A curvature analysis was performed on the master preparation scan, and the margin was extracted by selecting all points with a curvature >1.8. Right: The margin was then divided into sections representing mesial, distal, buccal and lingual.

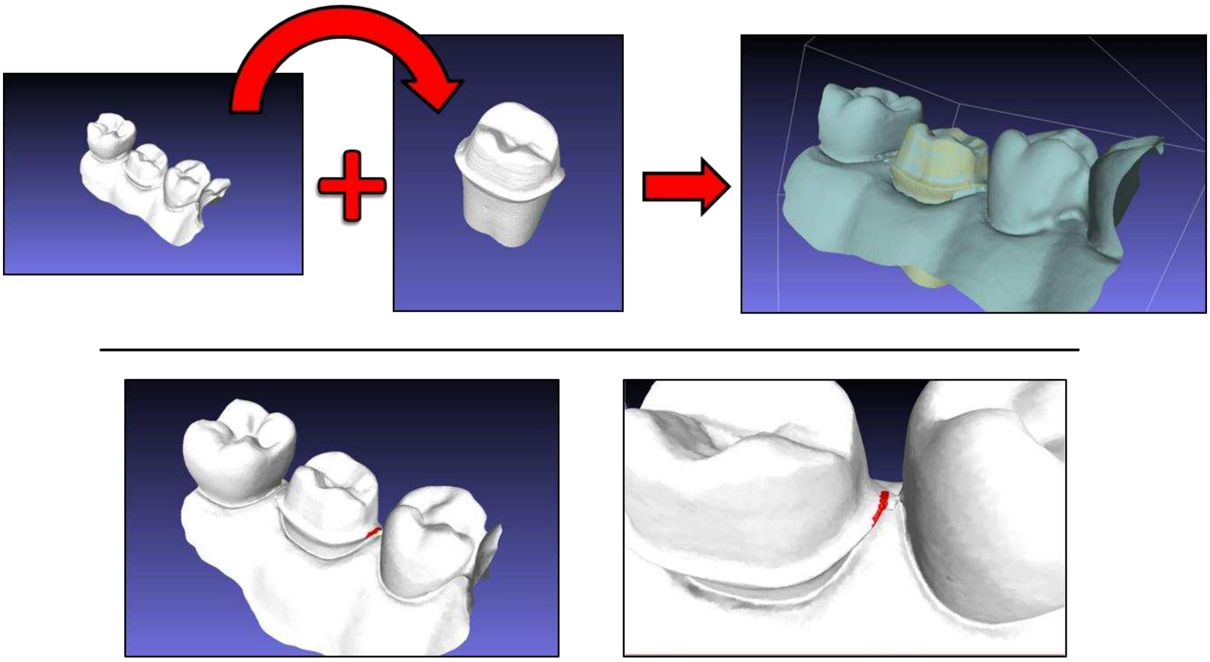

Figure 3 Aligning the IOS Scans to the Master Scan and Identifying the Margin Sections. Each IOS scan was aligned to the master preparation scan (top). The margin sections were then extracted by selecting all points lying within 100µm of the master margin sections. A mesial section is shown (bottom left). This method ensured that an accurate and consistent margin was found, even in cases where scanning artefacts made clear margin identification difficult (such as the 'bridge' to the 35 shown bottom right).

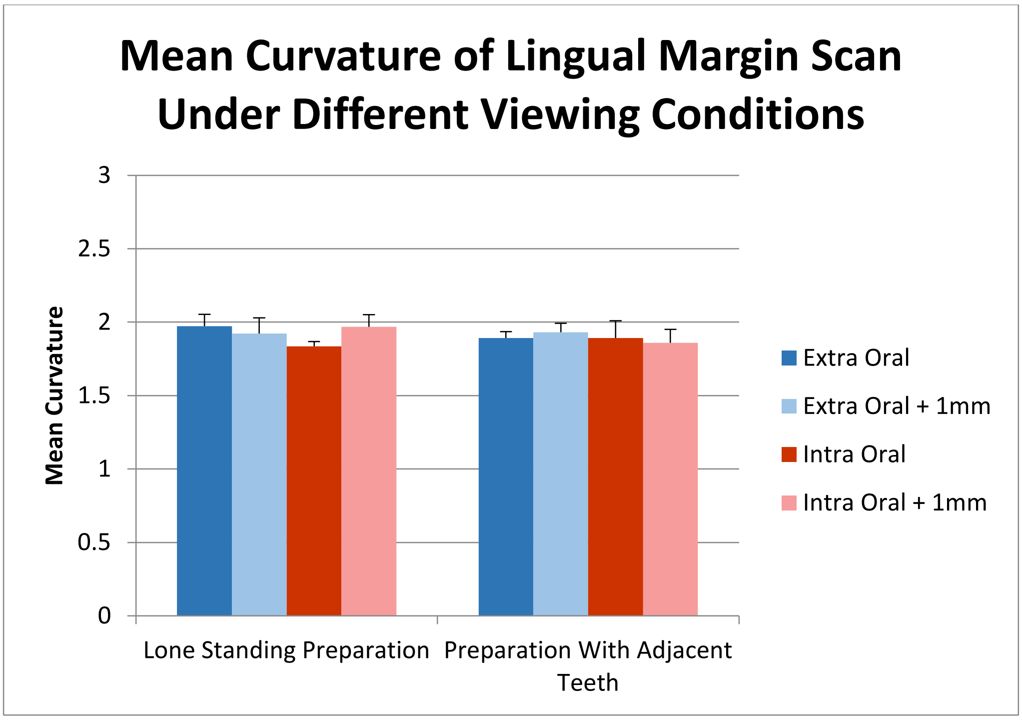

Figure 4 Effect of Confounding Factors on Curvature of Lingual Margin Section. The lingual margin was supragingival in all cases,1.5mm initially (blue), then raised to 2.5mm after remounting the tooth with the 1mm shim (red). Error bars represent one standard deviation.

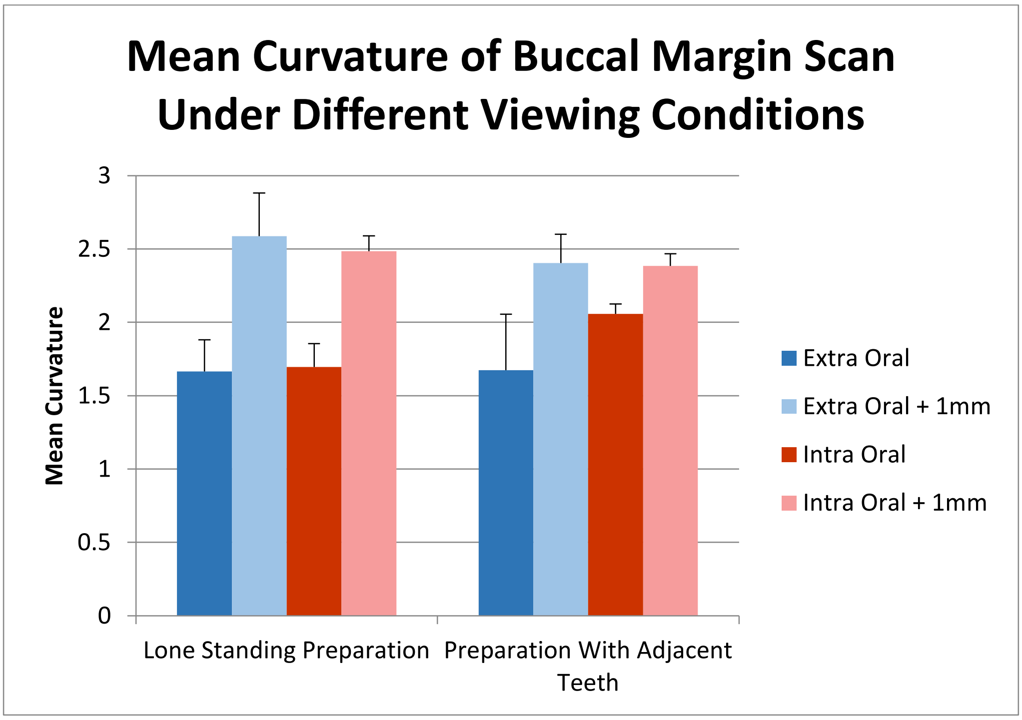

Figure 5 Effect of Confounding Factors on Curvature of Buccal Margin Section. The margin was initially equigingival (blue), then subsequently raised 1mm by remounting the tooth with the 1mm shim (red). Error bars represent one standard deviation.

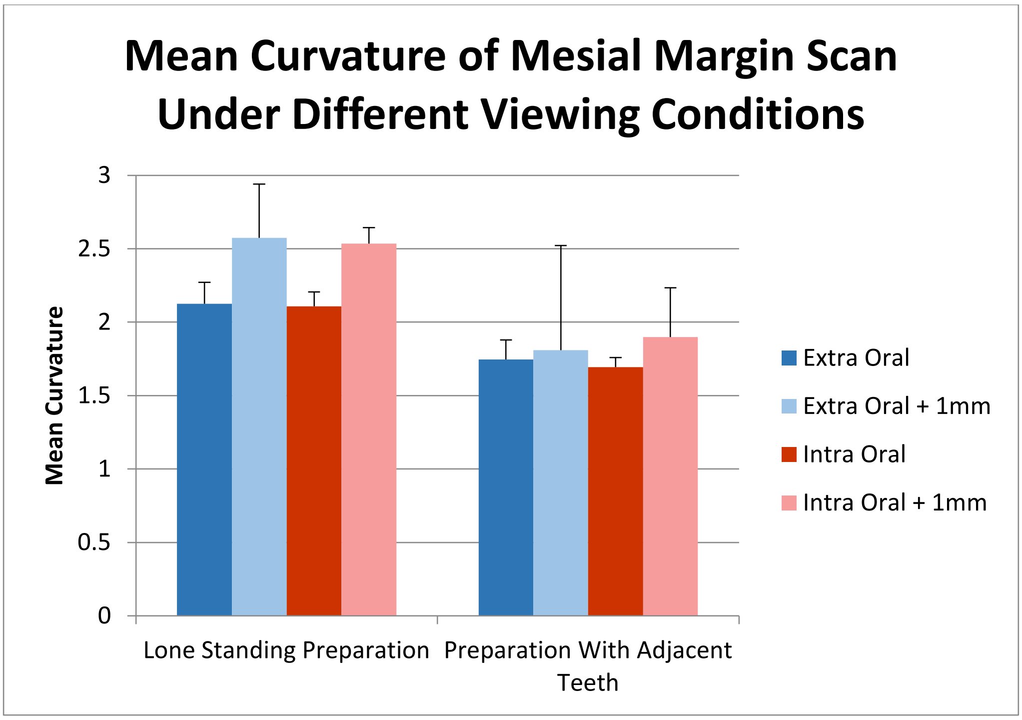

Figure 6 Effect of Confounding Factors on Curvature of Mesial Margin Section. The margin moved from equigingival buccally, to supragingival lingually (blue). It was then raised by 1mm by remounting the tooth using the 1mm shim (red). <u>Error bars represent one standard deviation.</u>

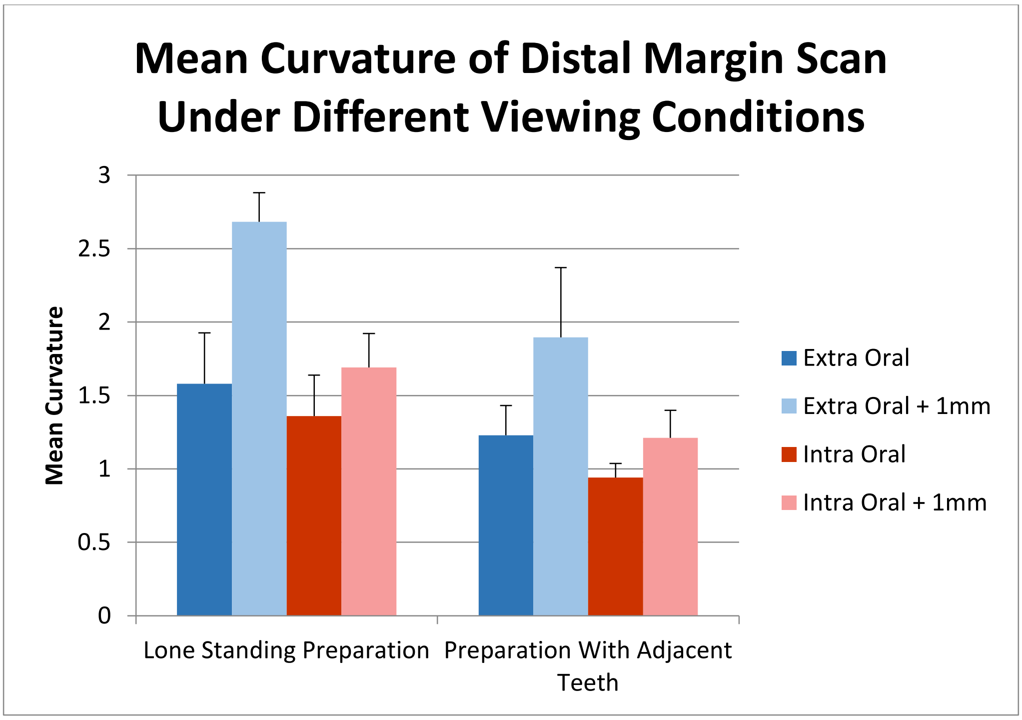

Figure 7 Effect of Confounding Factors on Curvature of Distal Margin Section. The margin moved from equigingival buccally, to supragingival lingually (blue). It was then raised by 1mm by remounting the tooth using the 1mm shim (red). <u>Error bars represent one standard deviation.</u>

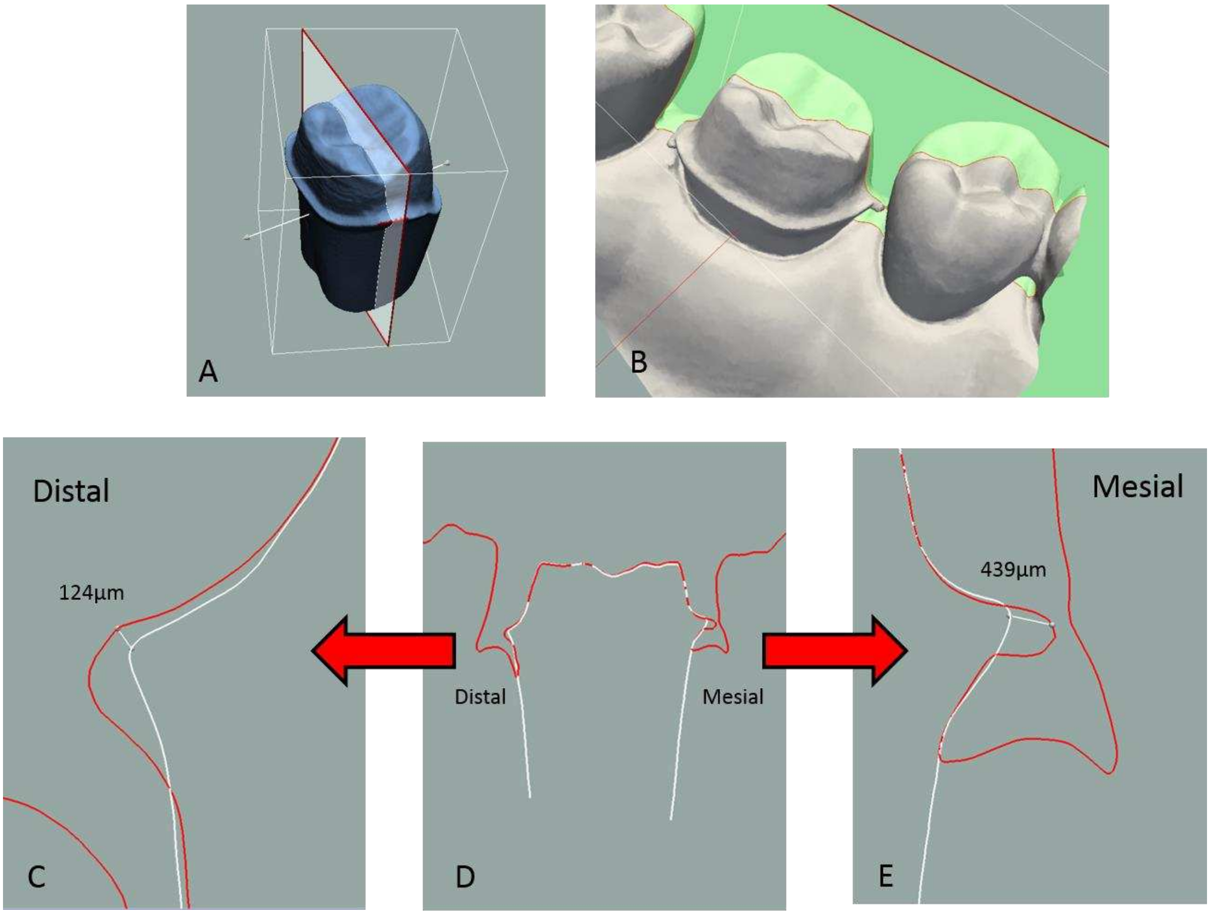

Figure 8 Example Scan. An example scan is shown (B). Here the adjacent teeth were *in situ*, the scan was taken intra-orally and a 1mm shim was in place to elevate the margin. The IOS margin shows bulging distally and a 'bridge' mesially (which merges with the adjacent tooth). Identical mesio-distal cross sections of the gold-standard dental model scan (A) and the IOS scan (B) are shown overlaid (D), and enlarged (C,E). The IOS margin (red) deviates from the correct margin (white).

Table 1 Mean Curvature for Lingual Margin Under Different Combinations of Confounding Factors.
(All entries are based on five repeated scans)

Lone Standing (Lone) or Adjacent Teeth (Adj)	Intra Oral (IO) or Extra Oral (EO) Scan	1mm Shim Inserted (+) or Not (-)	Mean Curvature	Standard Deviation	95% Confidence Interval	
Lone	EO	-	1.97	0.08	1.87	2.07
Lone	EO	+	1.92	0.11	1.79	2.05
Lone	IO	-	1.84	0.03	1.80	1.87
Lone	IO	+	1.97	0.08	1.87	2.07
Adj	EO	-	1.89	0.04	1.84	1.95
Adj	EO	+	1.93	0.06	1.86	2.01
Adj	IO	-	1.89	0.12	1.75	2.04
Adj	IO	+	1.86	0.09	1.75	1.97

Table 2 Mean Curvature for Buccal Margin Under Different Combinations of Confounding Factors.
(All entries are based on five repeated scans)

Lone Standing (Lone) or Adjacent Teeth (Adj)	Intra Oral (IO) or Extra Oral (EO) Scan	1mm Shim Inserted (+) or Not (-)	Mean Curvature	Standard Deviation	95% Confidence Interval	
Lone	EO	-	1.67	0.22	1.40	1.93
Lone	EO	+	2.59	0.29	2.22	2.95
Lone	IO	-	1.70	0.16	1.50	1.89
Lone	IO	+	2.48	0.10	2.36	2.61
Adj	EO	-	1.67	0.38	1.20	2.15
Adj	EO	+	2.40	0.20	2.16	2.65
Adj	IO	-	2.06	0.07	1.97	2.14
Adj	IO	+	2.38	0.08	2.28	2.49

Table 3 Mean Curvature for Mesial Margin Under Different Combinations of Confounding Factors. (All entries are based on five repeated scans)

Lone Standing (Lone) or Adjacent Teeth (Adj)	Intra Oral (IO) or Extra Oral (EO) Scan	1mm Shim Inserted (+) or Not (-)	Mean Curvature	Standard Deviation	95% Confidence Interval	
Lone	EO	-	2.12	0.15	1.94	2.31
Lone	EO	+	2.57	0.37	2.12	3.03
Lone	IO	-	2.11	0.10	1.99	2.23
Lone	IO	+	2.54	0.11	2.40	2.67
Adj	EO	-	1.75	0.13	1.58	1.91
Adj	EO	+	1.81	0.71	0.93	2.69
Adj	IO	-	1.69	0.07	1.61	1.78
Adj	IO	+	1.90	0.34	1.48	2.32

Table 4 Mean Curvature for Distal Margin Under Different Combinations of Confounding Factors. (All entries are based on five repeated scans)

Lone Standing (Lone) or Adjacent Teeth (Adj)	Intra Oral (IO) or Extra Oral (EO) Scan	1mm Shim Inserted (+) or Not (-)	Mean Curvature	Standard Deviation	95% Confidence Interval	
Lone	EO	-	1.58	0.35	1.15	2.01
Lone	EO	+	2.68	0.20	2.43	2.93
Lone	IO	-	1.36	0.28	1.01	1.71
Lone	IO	+	1.69	0.23	1.40	1.98
Adj	EO	-	1.23	0.20	0.98	1.48
Adj	EO	+	1.90	0.48	1.31	2.49
Adj	IO	-	0.94	0.10	0.82	1.06
Adj	IO	+	1.21	0.19	0.98	1.44