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Marginal Discrepancy Comparison Between Technician and Artificial Intelligence Utilizing Micro-CT

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ABSTRACT
Objective: The objective of this project is to assess the marginal fit of zirconia crowns designed by the 3Shape Automate Machine Learning CAD system to previously established acceptable values for marginal fit of zirconia crowns.
Methods: Twenty-Nine crown preparations were completed on a variety of posterior Dentoform teeth and the preparations were scanned via the Dentsply Sirona Primescan intra-oral scanner. Digital files of the scans were uploaded to Dentsply Sirona In-Lab software for digital die trimming and also to the 3Shape Automate program for CAD design for zirconia crowns with a return time of five minutes. The Automate CAD designs were then milled from Zenostar Translucent Zirconia pucks (98mm) and then sintered and sintered in), and the digital die files were printed using a Form 3B 3-D printer. The milled crowns and printed dies were then scanned without luting using a Skyscan 1172 micro-CT and marginal gap, discrepancy, and overhang were measured and analyzed from the image sequences.
Results: Total mean for marginal discrepancy (M=236um, SD = 81), overhang (M=212um, SD=101), and gap (M=84um, SD=21). When sample groups were compared between molar and premolar crowns, premolars showed a statistically significantly lower ($p = 0.001$) mean marginal discrepancy (M=203um, SD=41) than molars (M=250, SD=89). Premolar samples did have a lower percentage of marginal gap measurements that were clinically acceptable when compared to molars, but the difference was not statistically significant ($p > 0.05$).
Significance: When compared to the literature values for marginal fit of CAD/CAM zirconia crowns on chamfer margin preparations, the Automate system had a comparable marginal gap, but did show a greater mean overhang. The mean marginal gap for all samples was well within the range of clinical acceptability, indicating that 3Shape Automate would be an adequate adjunct to expedite the CAD/CAM process given the output time of machine learning as compared to manual margin and crown design without compromising accuracy of fit.

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Introduction

Speed and accuracy of intra-oral scanners in conjunction with computer aided design and computer aided manufacturing (CAD/CAM) have continued to improve over the last two decades[1-3]. As a result, their adoption, in conjunction with improvements in 3D printing technologies, has increased significantly in dental practices globally[4]. Patients have reported increased satisfaction with intra-oral scanner use for impressions over conventional impression techniques due to improved comfort and speed. In addition to improvement in the patient experience, intra-oral scanning for impressions of single unit fixed prostheses has shown to result in comparable marginal adaptation of the prosthesis to that of conventional impressions[5-9]. Marginal adaptation of fixed dental prosthetic restorations is one of the most vital to the long-term clinical success of the prosthesis. Marginal adaptation is measured utilizing two components: marginal discrepancy and marginal gap. Marginal gap is defined as the perpendicular measurement from the cervical margin of the restoration to the preparation margin, and marginal discrepancy is the angular combination of the marginal gap and the over/under extension of the restoration from the margin horizontally. Poor marginal adaptation can contribute to biofilm accumulation and increase the risk of secondary caries to the tooth with the restoration and/or approximating teeth[8,11-17]. Clinical studies have determined marginal gaps of 120µm or less to be clinically acceptable for cementing restorations and achieving good clinical outcomes as it relates to microleakage around the margins of restorations[16,18]. With improvements in accuracy and speed of imaging software helping improve clinical outcomes with the use of intra-oral scanners over the last decade, the next iteration of the digital workflow for use in fabricating fixed restorations is the incorporation of machine learning artificial intelligence. Artificial intelligence is the ability of computers to utilize tree-search algorithms and symbolic task planning to autonomously plan a sequence of action. Machine learning is distinguished by the ability of a computer program to utilize stored data sets to learn and self-improve from its own experience completing a task.

Significance

One of these branches of machine learning that is beginning to become incorporated in dental software programs is object recognition. Object recognition is a general term to describe a collection of related computer vision tasks that involve identifying objects in digital imaging[19-22]. 3Shape is an intra-oral scanner and CAD/CAM software development company that has produced the first clinically available object recognition software, 3Shape Automate, that utilizes machine learning to completely design posterior fixed dental prostheses from an intra-oral scan without human intervention in the identification of margins or design of the restoration. Prior to the development of this software, the operator of the CAD technology would have to identify and select the margins on the scanned preparation for the computer to fabricate an initial design of the prosthesis that is then adjusted by the operator. With the Automate software, a fully designed prosthesis is returned in as little as five minutes following upload of the intra-oral scan file into the software program.

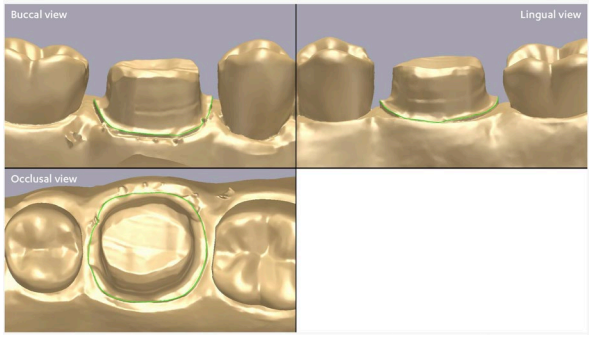

Figure 1: 3Shape Automate margin determination output

Purpose

Being a first in class machine learning program, we aimed to evaluate the discrepancy in margin detection between a human operator and the machine learning software with an in vitro setup. A comparison between previous micro-CT analyses of marginal fit studies for similar crown and margin types will be used to compare the capabilities of this 3shape Automate system to conventional CAD/CAM design methods. Previous studies have shown micro-CT to be an adequate adjunct to measure marginal fit accurately, especially as resolution in imaging has improved over time[23-25].

Hypothesis

The null hypothesis of this study was that there are no statistically significant differences in margin detection between the human operators and the machine learning software based on marginal fit and discrepancy values.

Methods

Development of Sample Preparations

Twenty-nine (29) tooth preparation samples were completed on a Columbia Dentoform (Long Island City, NY) model T-1560 typodont with a full complement of thirty-two ivorine teeth. The samples included in the study were eleven (11) maxillary molars, five (5) maxillary premolars, nine (9) mandibular molars, and four (4) mandibular premolars. Teeth were prepared with chamfer diamond burs under a timer of four minutes to minimize time dedicated to refinement of the preparation margins. Although thirty-five preparations were conducted, preparations were only included if they met the inclusion criteria below:

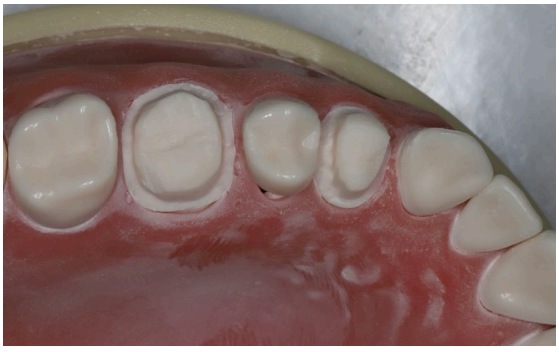

Figure 2: Posterior preparations completed on Columbia Dentoform Typodont per inclusion criteria

Figure 3: Typodont preparations scans via Dentsply Sirona Primescan intraoral scanner

1. Marginal width (axial reduction) of preparation >0.5mm and <2.0mm at narrowest and deepest part of preparation.
2. Total occlusal convergence not to exceed 30 degrees at most tapered aspect.
3. Axial preparation height at least 2.5mm or greater at all aspects of the preparation.
4. Preparations with retention boxes and grooves not to be excluded.
5. Finish line not to exceed 3mm supra-gingival or sub-gingival at highest and deepest aspect.

All 29 included samples were scanned along with the opposing dentition and a buccal image for bite registration utilizing the Dentsply Sirona Primescan scanner. Standard tessellation language (.stl) files of the preparation scan and opposing arch scan were exported for use in development of crowns and dies.

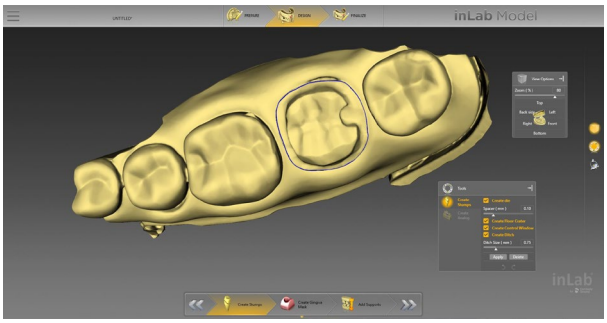

Figure 4: Technician margin determination for digital die fabrication via Dentsply Sirona In-Lab software

Production of die models

Fabrication of sample dies was completed via upload of sample .stl files to the Dentsply Sirona In-Lab Model software program. Digital die trimming was completed by a lab technician visually identifying the margin on the .stl model. Digital die .stl file was generated and submitted for 3D printing in Model V2 resin via a Form 3 printer (Form Labs).

Fabrication of Crowns Samples

3shape Dental System Order .zip files from the .stl preparation files were uploaded into the 3Shape Automate web portal. 3Shape Automate utilizes cloud based machine learning processes to return a CAD crown design within as little as five minutes from the upload. The set parameters utilized for all CAD crown designs was 0.03 mm contacts, 0.3 mm out of occlusion, and automatic removal of undercuts. The CAD crown design .stl files generated from the Automate program were uploaded into the 3Shape Dental System.
The crowns were then milled in an MCX milling machine out of a Pure shade Zenostar Translucent zirconia (Wieland Dental) puck and sintered to manufacturer standard.

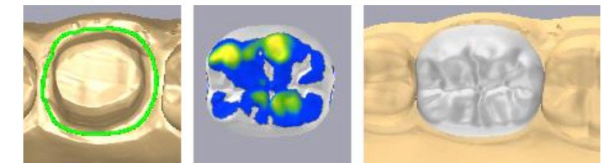

Figure 5: 3Shape Automate CAD crown output with final margin outline

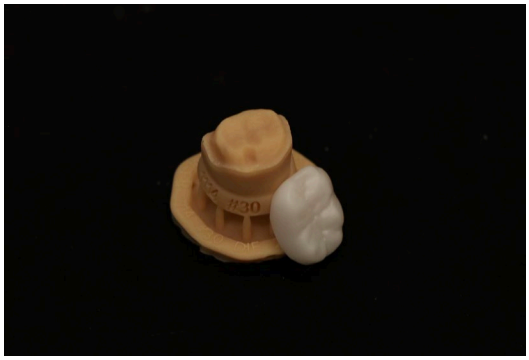

Figure 6: Die model from digital die trimming and milled Zenostar Translucent Zirconia crown from 3Shape Automate CAD file.

Sample Preparation for Analysis

Each crown specimen was placed on the corresponding printed die for evaluation of marginal gap and marginal discrepancy as defined by Holmes et al. under microcomputer tomography (micro-CT). Scans were completed on a Skyscan 1172 micro-CT with a view of 2000x2000 pixel bitmap (BMP) and pixel size of 9.9 µm. Due to large discrepancy of the radiopacity and density of the zirconia crowns compared

to the resin dies, a scan with the crown on the die was conducted at 75kV, 134uA, 10W utilizing a 0.5mm Al+ filter and a separate scan of the die with the crown removed at 45kV, 222uA, 10W utilizing no filter. Care was taken when removing the crown to not mobilize the die so that the separated scans could be overlaid with accuracy.

Individual micro-CT images were reconstituted into an image sequence for the separate die and crown scans. A 3D registration of the reconstituted image sequences was completed using the Dataviewer 1.4.4 software program. The crown sequence was registered as the target registration and the die sequence was registered as the reference registration, allowing the ImageJ Java based image processing program to merge the two registrations together into one combined image sequence using the program's image calculator. The merged image sequence was registered as a coronal view image sequence in the Dataviewer software program and this final registered image sequence was uploaded into the Bruker CTAn software for image analysis.

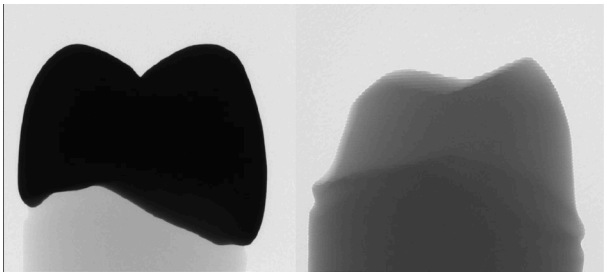

Figure 7: Skyscan 1172 of crown on die model at 75kv, 134uA, 10W under 0.5mm Al+ filter (left) and of die model with crown removed at 45kV, 222uA, 10W under no filter (right).

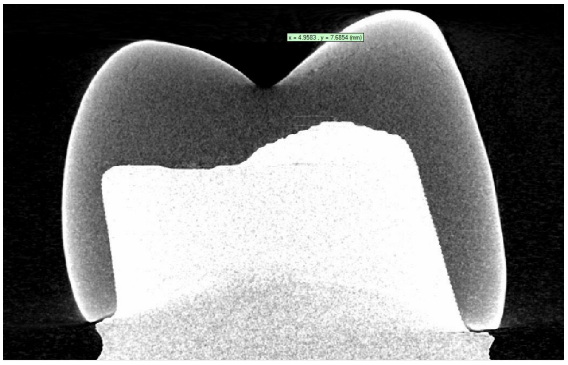

Figure 8: Merged crown and die micro-CT scans (coronal) view) in Bruker CTAn software for measurement analysis

Data Analysis

Six measurements for marginal gap and marginal discrepancy were measured on the coronal image sequence of each sample. Three image slices were selected at each quartile of the image sequence and measurements were made on the mesial and distal per image slice analyzed. This study utilized the Holmes et al. [16,26] definition of marginal gap as the perpendicular measurement from the cervical margin of the crown to the preparation margin, and marginal discrepancy as the angular combination of the extension error (overextension) and the marginal gap (Figure 9).

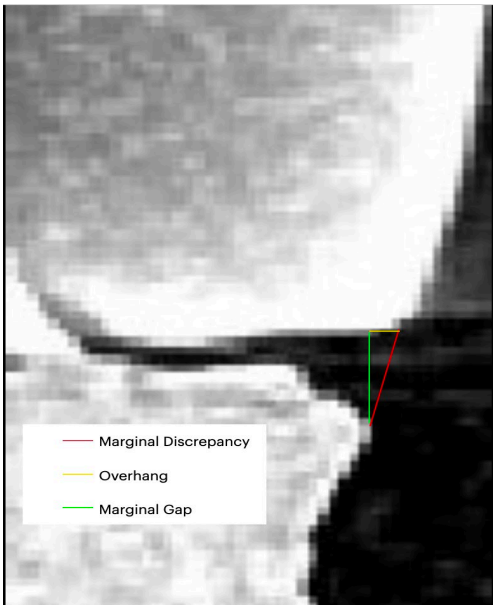

Figure 9: Sample view showing measurements made per coronal slice of the micro-CT image sequence.

Results

Mean assessment of all samples as it relates to marginal gap, marginal discrepancy, and overhang were all determined collectively and separately based on tooth morphology (molar vs. premolar). Mean marginal discrepancy for all samples was 236 µm (sd = 81um), with mean overhang of 212 um (sd =101um), and mean marginal gap of 84 um (21 um). Values for these measurements separated by tooth morphology are outlined in Table 1. The marginal discrepancy was

significantly larger (p=.001) for molar samples than premolar samples (Figure 10). All other assessments of fit when comparing tooth morphology were not significant. Although premolars had a significantly smaller marginal discrepancy, a higher percentage of measurements (31.3%) were deemed clinically unacceptable in regards to marginal gap compared to molars (18.3%).

The literature defines clinical acceptability for marginal gap to be <120 um. However, the difference in clinical acceptability of marginal gap between the two groups was not significant (p=0.068) (Figure 11).

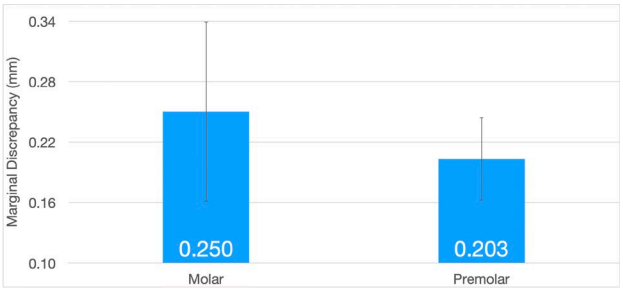

Figure 10: Mean comparison for marginal discrepancy between molar and premolar samples (p=0.001)

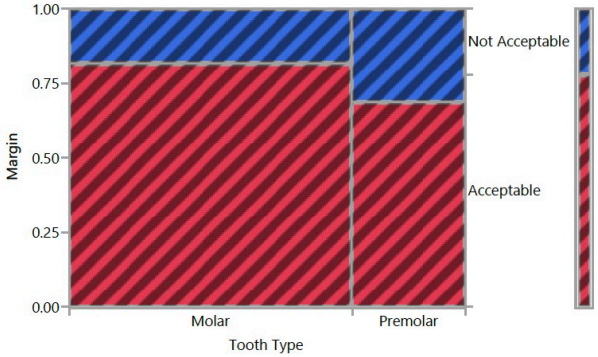

Figure 11: Chi Squared assessment of molar vs. premolar sample measurements based on clinically acceptability using 120um as the reference value.

Table 1. Marginal Fit Characteristics, M (SD) um

Tooth Morphology Type	Marginal Discrepancy	Marginal Overhang	Marginal Gap
All Samples	236 (81)	212 (101)	84 (21)
Premolars	203 (41)	201 (114)	86 (22)
Molars	250 (89)	214 (97)	82 (21)

Discussion

Given how the study was designed, a direct assessment of the accuracy of the 3Shape Automate system could not be established, but future studies could utilize the results of this study to better assess a machine learning system itself. However, for potential utilization of the 3Shape Automate program to be expedited as CAD design software for a high volume setting like the Defense Health Agency clinics, it is important for clinicians to be able to approximate how the program performs in relation to their own CAD designs as it relates to marginal adaptation of the restorations.

Although the dental literature is inconclusive on what is clinically acceptable in regards to overhang and marginal discrepancy, a study of CAD/CAM Zirconia crowns with chamfer margins found that the average overhang was determined to be 104 um[27]. The results of the analysis of this study, which also uses zirconia crowns with chamfer margins, the overhang average of 236 um appears to be above what is to be expected. However, we cannot make a definitive assessment that the machine learning

program/algorithm over-estimates the margin placement, as this discrepancy could be due to continuous under-estimation of the margin by the technician and/or discrepancy due to the file conversions from the Primescan to the 3Shape Automate program. However, from the data, a clinician can reasonably expect an increase in overhang when utilizing 3Shape Automate system as compared to the average technician margin.

The same prior study of CAD/CAM Zirconia crowns with chamfer margins when assessing marginal gap had a result of 68 um average from their sample set. The sample set from this study determined to have a similar average marginal gap of 81 um[27], indicating that machine learning software discrepancy is similar to that of a human technician as it relates to the marginal gap. Discrepancies could occur again when printing the die model from the .stl file and when converting the original scan to the .stl file. However, 81 um marginal gap remains well within the clinically acceptable marginal gap range of <120 um[16,18].

The significant difference in the marginal discrepancy between the premolar and molar crowns can most likely be assumed to relate to the greater surface area of the margins of molars. This greater surface area likely increases the probability of error in margin identification by the Automate system over a greater area. Additionally, given that preparations were prepared in the same time limit, more time for smoothing of margins could be dedicated to the premolars that have a smaller surface area to be prepared. The mean marginal gaps for premolars and molars was very similar, although the premolar sample group had a higher percentage of margin points that were clinically unacceptable that can likely be attributed to smaller sample size and random error.

The study could have been improved by utilizing the originally prepared teeth to compare the fit of the crowns between the original preparation and the die models. However, this study design can be utilized as a pilot methodology for assessing marginal fit of the Automate designs on live patient tooth preparations given that the original preparation is retained by the patient and unavailable for analysis. Notably, the sintering process of the zirconia crowns causes some shrinkage discrepancy and the polycrystalline structure is too radio-opaque for the micro-CT to adequately penetrate. In further studies lithium disilicate crowns would be better utilized for assessment as the radiopacity is more compatible with the resin die models.

Conclusion

This study shows that the 3Shape Automate machine learning program is comparable in terms of marginal fit to that of published values for zirconia crowns placed on chamfer finish lines. The overhang was notably larger than the published average. Additionally, this study indicates that the margin determination of the Automate program is more accurate on premolars than molars.

More research needs to be done to assess the accuracy of the Automate CAD designs especially as similar machine learning programs develop and improve. The protocol would best be utilized using previous patient scans to best assess how the machine interprets differences in biologic tissue on live preparations and its resultant effect on marginal fit. This study also shows the benefits of using a micro-CT to best assess marginal fit of indirect restorations.

Disclaimer

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Disclosures

The authors disclose that they have no financial gain or affiliations with any company or product used in this research.

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Author Contributions

Aaron Gringer conceived the study concept, collected the data and wrote the manuscript. Dr. Wen Lien DMD, MS analyzed the data and provided the laboratory equipment utilized in the study.

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