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Accuracy of Intraoral Scanners with Different Total Occlusal Convergence Angles: An In-Vitro Study

Brittany M. Pang

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LOMA LINDA UNIVERSITY
School of Dentistry
in conjunction with the
Faculty of Graduate Studies

Accuracy of Intraoral Scanners with Different Total Occlusal Convergence Angles: An In-Vitro Study

by

Brittany M. Pang

A Dissertation submitted in partial satisfaction of
the requirements for the degree
Masters of Science in Periodontics

May 2019

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Each person whose signature appears below certifies that this thesis in his/her opinion is adequate, in scope and quality, as a thesis for the degree Masters of Science in Periodontics and Implant Surgery.

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ABBREVIATIONS

TOC	Total occlusal convergence
PEMA	Poly(ethyl methacrylate)
STL	Stereolithography
LED	Light-emitting diode
CMF	Cranio Maxillo Facial
CAD/CAM	Computer-aided design and computer-assisted manufacture
Tru Def	True Definition® (3M Espe, St. Paul, MN, USA).
µm	Micrometer
mm	Millimeter
ANOVA	Analysis of variance

ABSTRACT OF THE THESIS

Accuracy of Intraoral Scanners with Different Total Occlusal Convergence Angles: An In-Vitro Study

by

Brittany M. Pang

Masters of Science, Graduate Program in Periodontics and Implant Surgery
Loma Linda University, May 2019
Dr. Erik Sahl, Program Director

Digital intraoral imaging has become more utilized in contemporary dental practice. This is performed using an intraoral scanner and it can be used as an alternative to making conventional impressions when indicated. This technology has many advantages, such as decreasing the number of appointments by eliminating traditional techniques, along with a reduction of laboratory time and improved patient comfort. The accuracy of intraoral scanners is currently being assessed in various aspects. To our knowledge, no study has yet addressed the accuracy of intraoral scanners in regards to total occlusal convergence (TOC) of complete coverage of anterior and posterior preparations in the presence of adjacent teeth. Data was collected by scanning a standard dental typodont affixed on a manikin. The aim of this study was to compare the accuracy (precision and trueness) between two intraoral scanners of an affixed typodont on a manikin, comparing different angles of total occlusal convergence of one anterior and one posterior complete coverage all-ceramic tooth preparations. A second objective was

to evaluate the influence of location of tooth preparation relative to the arch position (anterior v. posterior).

This study was performed on a printed poly(ethyl methacrylate)(PEMA) model of an affixed typodont on a manikin with two different anterior and posterior complete coverage all-ceramic crown preparations (Teeth #9 & #15). Each preparation incorporated -8, 0, 8, 16 and 22 degrees of TOC as a retrievable printed PEMA die preparation. A reference desktop scan was taken of each of the die preparation models using the D900L (3Shape) desktop scanner, which was then used as the control. Each die model was then placed in the typodont and the typodont was subsequently affixed to a manikin. 10 sample scans were taken of each preparation with each intraoral scanner, the Trios 3Shape Intraoral scanner and True Definition Intraoral scanner. The reference and intraoral scans were then saved as stereolithography (STL) files. The intraoral scans were compared to the specific reference desktop model. Surface to surface registration was then conducted in order to overlay the samples with the control using Geomagic Control X version 2018.1.1 (3D Systems) was performed in order to obtain the best fit alignment of the evaluated tooth preparation to its corresponding control tooth preparation. Trueness was determined through the significance in the mean distance discrepancy of the desktop scan and intraoral scan. Precision was determined through the standard deviation of each scanner for each die preparation. Both trueness and precision were used to determine the accuracy of each scanner.

There will be no significant difference in the accuracy of the Trios 3Shape intraoral scanner to the True Definition intraoral scanner when comparing total occlusal convergence angles of -8, 0, 8, 16 and 22 degrees for complete coverage tooth preparations. In addition, there will be no significant difference in the accuracy of both scanners in terms of the arch location of each preparation. Implementation of an affixed typodont on a manikin when using the intraoral scanners and comparison of total occlusal convergence angles of complete coverage preparation in the presence of adjacent teeth of a typodont have not been evaluated.

This study concluded that the Tru Def Scanner revealed more accuracy compared to the Trios scanner for all variables under the conditions in this study. Anterior preparations were less accurately read by the scanners than for the posterior preparations. Parallel preparations were the least accurate for the anterior tooth and undercut preparations were the least accurate in the posteriors. Overall, the decrease in taper decreased the accuracy of intraoral scanners, however, this was not clinically significant. Further clinical studies need to be carried out to confirm the findings of this study.

CHAPTER ONE

Introduction

The use of digital imaging is becoming more utilized in the dental world. Technology has continued to evolve in dentistry and the computer-aided design, and computer-assisted manufacture (CAD/CAM) has had an important role in dentistry since 1971.[1] Computer-aided design/computer-aided manufacturing (CAD/CAM) technology can be used to design crowns, bridges and dental digital impressions as well as 3D facial recognition, custom hearing aids, and plastic surgery.[2] The dentition can be scanned either directly or indirectly through the use of optical scanners to produce a digitalized image to manufacture crowns, bridges, or surgical guides by scanning the entire arch. Indirect scans performed extraorally can be digitized for similar purposes.[3] The precision of dental scanners has been thoroughly researched for operative dental usage.[4,5,6,7] Intraoral scanners can be utilized to produce well-fitting restorations.[8] This type of technology decreases the number of appointments by skipping traditional steps which may include taking a conventional impression, pouring up a cast and sending it to the lab for production.[7] Dentists that utilize the advantages of technology have the potential to improve the efficiency in the dental office. The effectiveness of digital imaging for fabricating implant supported crowns can minimize the amount of time by a third for the clinician.[9] Jeon et al used the blue light-emitting diode (LED) desktop scanner that served as the control in their study because of its high precision between multiple scans of the stone models compared to their polyvinyl siloxane impression.[10] Mejía et al compared the accuracy of total occlusal convergence angles from -8 to 22 degrees between conventional impressions and digital imaging of a partially edentulous typodont.[11] This study was able to achieve a specific degree of taper for each preparation using CAD software. Results demonstrated that TOC angles close to 0 degrees cannot be consistently replicated with conventional dental impressions. However, digital imaging was able to accurately scan abutment teeth regardless of the TOC angulation. Because this study had no adjacent teeth next to the prepared teeth and since the scans were done on a bench, the intraoral scanner was able to angulate and capture the prepared tooth in its entirety, which was a significant limitation in this study. This allowed the scanner to capture the die at all angles and regardless of the taper of the tooth preparation, increase in accuracy. This is impossible to replicate in a patient's mouth and a better scenario would be to place the die in a model and affixing it to a typodont for better validation of their study.

Bohner et al evaluated and compared the trueness of intraoral (Trios™, Cerec blue cam) and extraoral (D250 and Cerec InEosX5 lab) scanners in scanning prepared teeth. They found a higher frequency of discrepancies in the cervical region and on the occlusal surface. Their conclusion demonstrated that intraoral and extraoral scanners showed similar trueness in scanning-prepared teeth. While trueness was evaluated, a limitation of this study was the lack of evaluation of precision. They also included a single tooth preparation with a single adjacent tooth without rationalizing the reason behind this design. The authors suggested that the shape of the prepared tooth might influence scanning accuracy. However, it was not within the confines of this study to differentiate the accuracy of different tooth preparations. Furthermore, the study suggested the need for future research comparing the accuracy of scanning anterior and posterior teeth in order to validate such findings.[12] Hence, we will be comparing the accuracy of anterior and posterior tooth preparations as a secondary objective in this study.

Past studies have not implemented an affixed typodont on a manikin when using the intraoral scanners nor compared total occlusal convergence angles of complete coverage preparation in the presence of adjacent teeth of a typodont. Therefore, the aim of this study was to compare the precision and trueness between two intraoral scanners of an affixed typodont on a manikin, comparing various angles for total occlusal convergence of a complete coverage metal ceramic teeth preparations with the presence of adjacent teeth.

CHAPTER TWO

Material and Methods

This study utilized a desktop lab scanner (D900L, 3Shape, Copenhagen, Denmark) which served as the control and two intraoral scanners, the Trios 3® (3-Shape, Copenhagen, Denmark) and the True Definition® (3M Espe, St. Paul, MN, USA). The D900L (3Shape) desktop scanner uses blue LED and four high resolutions five-megapixel cameras and produces a color scan. It demonstrates 6.9 ± 0.9 micrometers of crown and bridge accuracy and 8 μm of implant bar accuracy. This serves as the reference model with zero error.[13] Trios 3Shape is an optical scanner that uses structured light and exhibits less than 8 μm in scanner accuracy. It works by creating a grid of light and captures disturbances within the grid when the light encounters the object. It is a handheld device with a camera at the end of a wand that generates pictures that are transported to the screen. The wand is moved intraorally utilizing confocal microscopy and optical scanning until all images of the arch are captured and then is uploaded as an STL file.

True Definition is a blue light intraoral scanner that uses structured light. The scanning tip is smaller than that of the Trios 3Shape using active wave-front sampling when capturing the monochrome images of the typodont. The model is then scanned after placing a thin layer of titanium oxide powder. According to Nedelcu and Persson, it was demonstrated that coated scanners were more accurate than non-coated scanners, with excessive coating not affecting the accuracy.[5] The images were transferred as a proprietary file and then transformed into an STL file. The True Definition intraoral scanner has a trueness of 61.4 μm and precision of 19.5 μm.[13]

Limitations of an intraoral scanner, that utilizes structured light, are inaccuracies in the presence of negative space or shiny surfaces. Negative space is more challenging to capture with the scanner, where sometimes it needs to be rescanned in order to capture the image in its entirety. One method to counteract this issue is the application of titanium dioxide powder or use a non-reflective material such as poly(ethyl methacrylate)(PEMA). A printed PEMA model of a maxillary typodont (Columbia Dentoform®, NY, USA) with five different complete coverage maxillary anterior and molar preparations were utilized for this study. The typodont and die preparations were then fabricated into a 3D printed model using an industrial scanner from In-Tech Industries (MN, USA) using iPro™ SLA® systems technology.

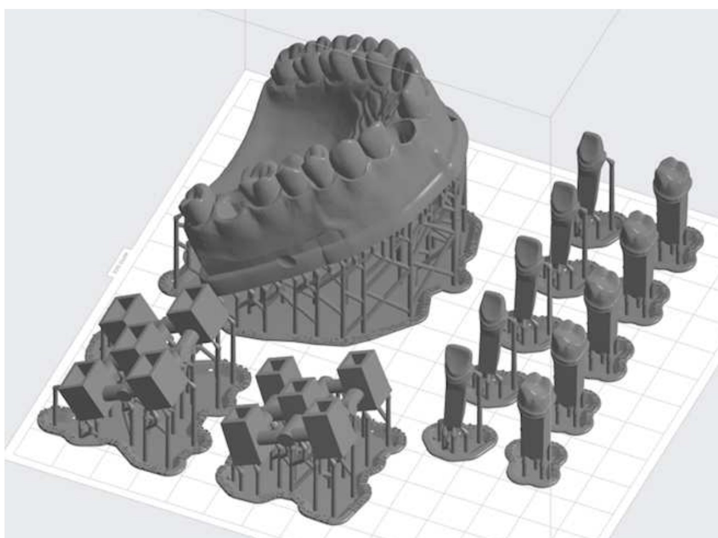

Figure 1. Diagram of 3D printed models

Two different complete all-ceramic tooth preparations were evaluated. The teeth preparations were performed for tooth #9 & tooth #15 and each incorporated -8, 0, 8, 16 and 22 degrees of TOC as demonstrated in the figure below.

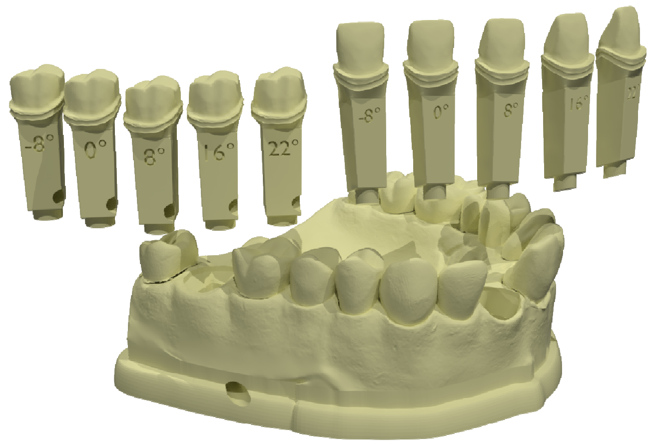

Figure 2. Diagram of the die preparations of -8, 0, 8, 16 and 22 degrees of TOC alongside the typodont.

The tooth preparations were also a retrievable printed PEMA die preparation. The TOC was standardized by digitally fabricating the preparations using Blender 3D, which is similar to CAD software[11] but is an open source 3D modeling software. A feature of this software is that it incorporates control of the TOC by allowing model tooth preparations to be formatted to the desired TOC by creating specific tapers through measuring the plane angles of the preps and fabricate each preparation as a die. It then was exported as an STL file to Meshmixer and is designed to be inserted into the typodont model.

A reference desktop scan was taken of each of the die preparation models using the D900L (3Shape), which served as the control and saved as an STL file. Each die model was then placed in the typodont and mounted to a dental operatory chair's headrest and subsequently affixed to a manikin. The manikin was aligned to simulate a 'live' patient situation during clinical conditions, which represented a fixed semi-supine position. This was done to simulate the teeth's position in a clinical environment. Ten sample scans were taken of each die with the Trios 3Shape Intraoral scanner and True Definition Intraoral scanner. A single calibrated examiner took the scans and assessed for precision and trueness. The primary investigator underwent a training and calibration period with an expert to ensure that the investigator demonstrated technical capability of achieving reliability in the study. Calibration involved the investigator achieving a minimum Intraclass Correlation Coefficient value of 0.90 with measurements made by the expert.

The True Definition intraoral scans were first transferred as a proprietary file, which was then transformed into an STL file. The Trios 3Shape and True Definition Intraoral scans were then saved as an STL format and opened in Geomagic Control X (3D Systems, MA, USA) to compare the STL reference desktop scan of the die to the 10 STL intraoral scans of that same die mounted to the typodont by superimposing it using surface to surface registration. This was done with each subsequent die. Geomagic Control X was performed in order to obtain the best fit alignment of the evaluated tooth preparation to its corresponding control tooth preparation. Trueness was be determined through the significance in the mean distance discrepancy of the desktop scan and intraoral scan.[13] Precision can be defined as the deviance measurement between a test and control or is the exactness of an object being measured and repeated.[4] Precision was determined through the standard deviation of each scanner for each die preparation. Both trueness and precision determined the accuracy of each scanner.[14] The superimposition of the 3D models produced color histogram mapping, which showed surface distance displacements against the desktop scan. Absolute distances with standard deviation and mean were then calculated for the sample error.

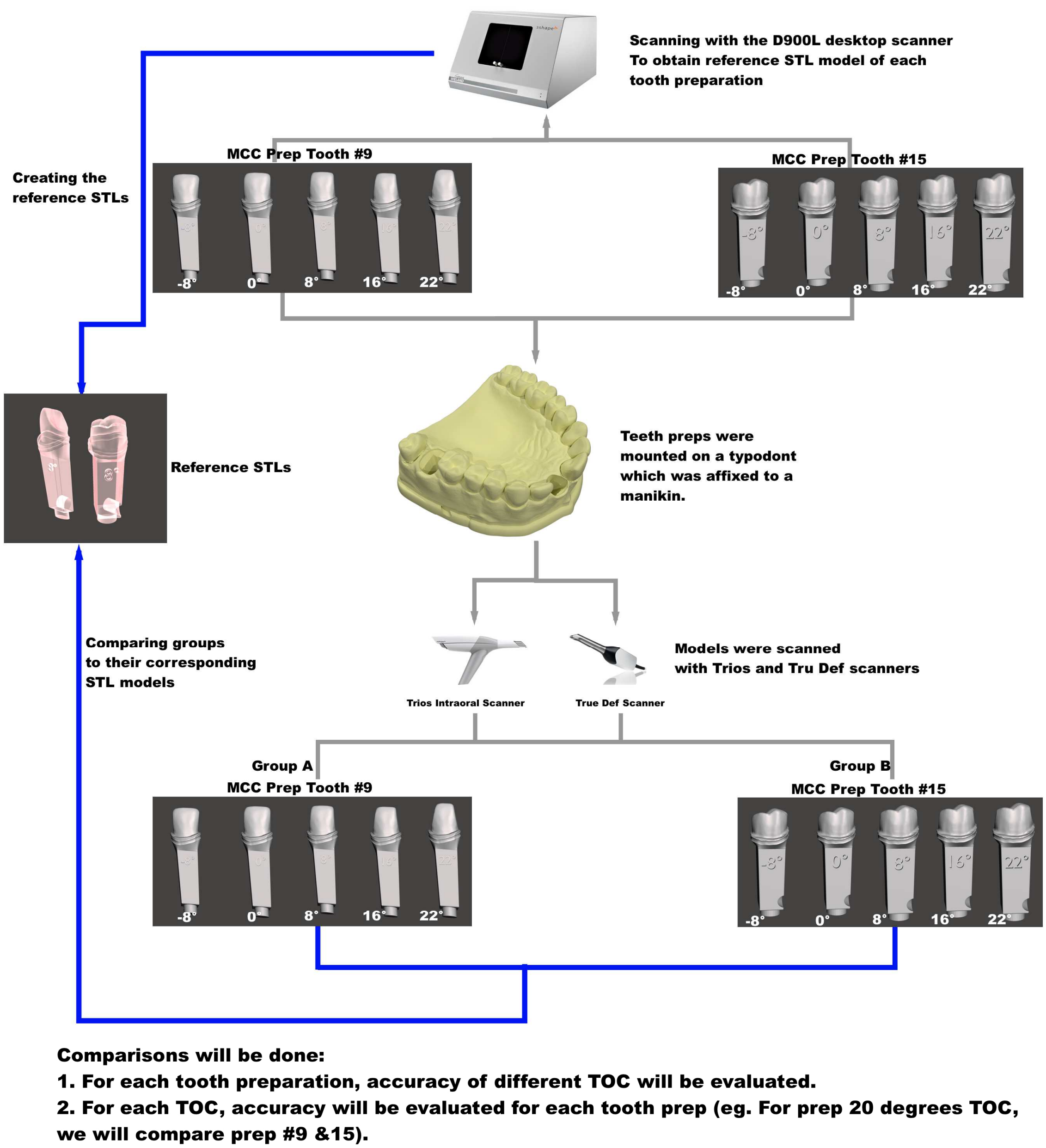

Figure 3. Illustration demonstrating study design workflow.

The limitations of the CAD/CAM technology shown in "Accuracy of Intraoral and Extraoral Digital Data Acquisition for Dental Restorations", was that the shape of the tooth might affect the accuracy of the scan. Rudolph et al showed that steep and parallel incisor surfaces were harder to capture when performing a digital scan. [15] In this study, the most challenging location for the 3Shape to capture was the sharp edges at the base of the cast. It also focused on minimizing reflection of the cast by sandblasting the surface. The 3Shape machine had a difficult time capturing the edentulous part of the cast, possibly due to the smooth surface of the cast.

Statistical Analysis

Ten scans were taken for each degree of TOC for the die preparation of tooth #9 & tooth #15 when mounted in a typodont. The scans were performed with the Trios 3Shape and True Definition intraoral scanners and each scan generated an STL file. These images were then overlaid onto the mate of the desktop scanned image using transform alignment and best-fit algorithm in Geomagic Control X. Using the same software, color mapping was done using the 3D compare feature and a report was generated for each die. The report included the average positive and negative discrepancies as well as the maximum positive and negative discrepancies. The absolute distances with mean and standard deviation for the sample error will be calculated and 95% confidence interval will be determined. The tolerance in this study was set to 50 µm.

Reliability of the examiner scanning in the study was assessed with a random sample of 30% of the study measurements. Reliability was assumed to have been achieved with Intraclass Correlation Coefficient values of 0.90 or greater. Using the Independent Sample t-test, 10 subjects per group will provide 90% power to detect a 6 µm difference in the study outcome variable average positive discrepancy between the two groups assuming a standard deviation of 5 µm.

The absolute discrepancy was obtained from the average negative discrepancy by multiplying it by (-1) then added to the average positive discrepancy which was then divided by the sum of 2. This was also done in Vandeweghe et al's study because negative and positive values would compensate for each other, which would falsely improve the outcome, therefore absolute values were used. [16]

Equation below:

Absolute discrepancy = (Positive Discrepancy + (-1 X Negative Discrepancy))/2

CHAPTER THREE

Results

The Wilcoxon Signed-Rank Test was performed to compare the difference between tooth #9 versus tooth #15 for both Trios and Tru Def scanners. Also, the same test was utilized to compare the performance of the Trios scanner versus the Tru Def scanner as demonstrated in Figure 4.

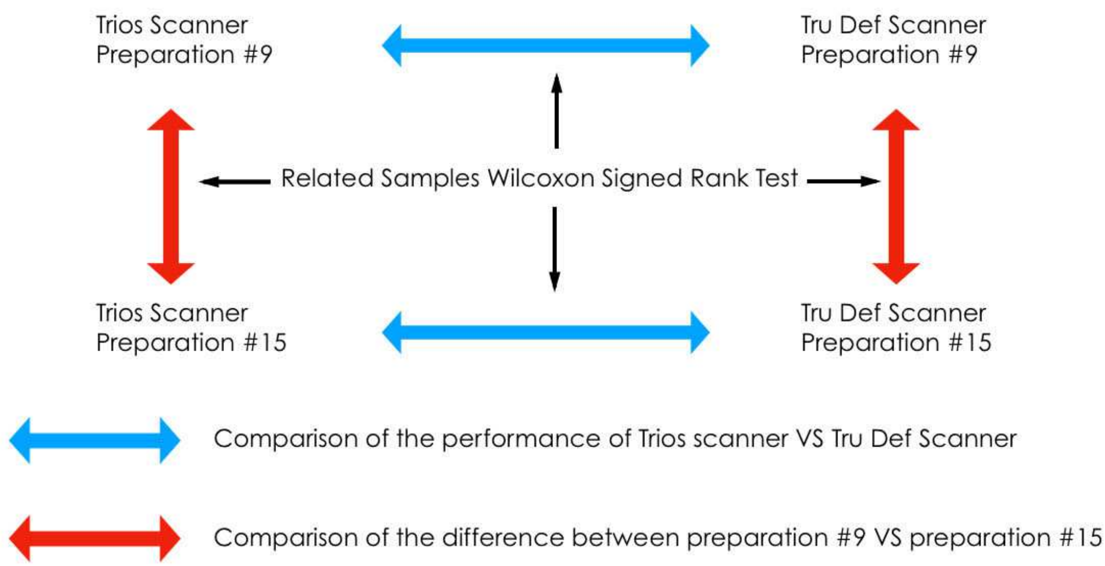

Figure 4. The Wilcoxon Signed-Rank Test analysis between the 4 main groups: Trios #9, Trios #15, Tru Def #9, Tru Def #15.

Table 1. Difference between the anterior (#9) VS posterior (#15) preparations for the Tru Def scanner

ScannerType = Tru Def

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The median of differences between Prep 9 (Avg Discrepancy) and Prep 15 (Avg Discrepancy) equals 0.	Related-Samples Wilcoxon Signed Rank Test	.000	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Table 2. Difference between the anterior (#9) VS posterior (#15) preparations for the Trios scanner

ScannerType = Trios

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The median of differences between Prep 9 (Avg Discrepancy) and Prep 15 (Avg Discrepancy) equals 0.	Related-Samples Wilcoxon Signed Rank Test	.000	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Difference between two anterior (#9) VS posterior (#15) preparations:

The Wilcoxon Signed-Rank Test was performed to measure the difference in trueness and precision between prep #9 and prep #15 as indicated by Table 1 and Table 2. There was a significant difference between both anterior and posterior prepped teeth (#9 and #15) with tooth #15 having better results than tooth #9.

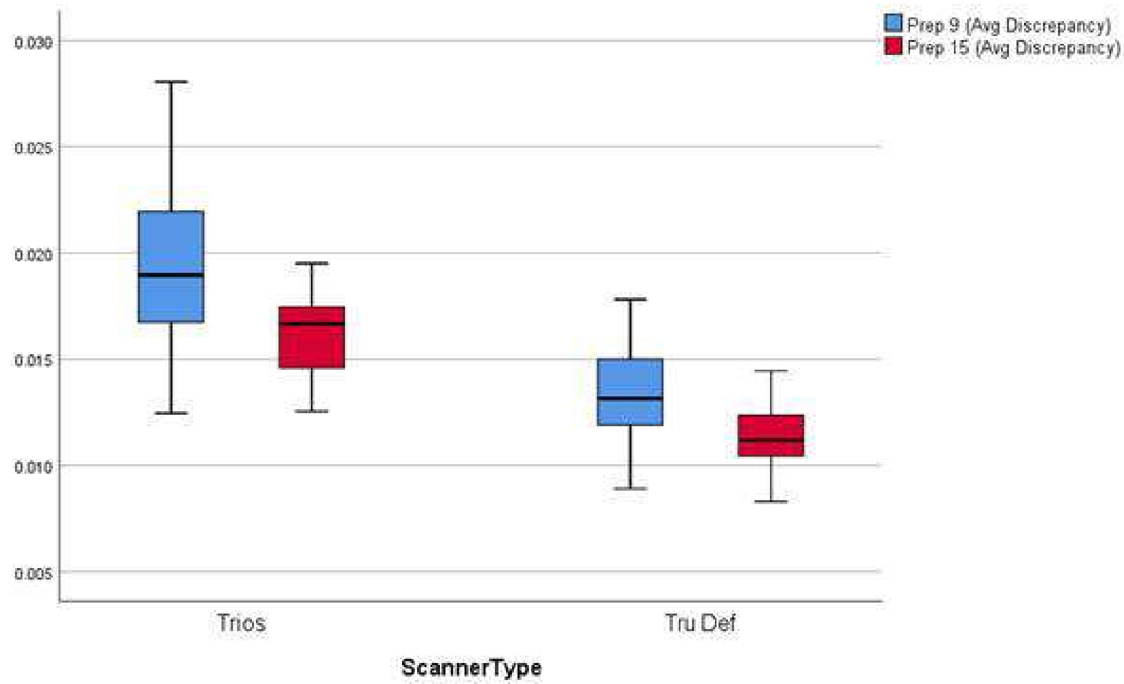

Figure 5. Boxplots showing the difference of accuracy of prep #9 and prep #15

Table 3. Difference between the Trios scanner and Tru Def scanner for tooth #9

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The median of differences between Prep 9 (Avg Discrepancy)_Trios and Prep 9 (Avg Discrepancy)_TruDef equals 0.	Related-Samples Wilcoxon Signed Rank Test	.000	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Table 4. Difference between the Trios scanner and Tru Def scanner for tooth #15

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The median of differences between Prep 15 (Avg Discrepancy)_Trios and Prep 15 (Avg Discrepancy) _TruDef equals 0.	Related-Samples Wilcoxon Signed Rank Test	.000	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Difference between the precision and trueness of both scanners (Trios and Tru Def):

The Wilcoxon Signed-Rank Test was performed to measure the difference in trueness and precision of both scanners. For both preparations, the data was grouped based on the scanner type (#9 and 15) as shown in Table 3 and Table 4. There was a significant difference between both scanners with the Tru Def scanner having better results than the Trios scanner.

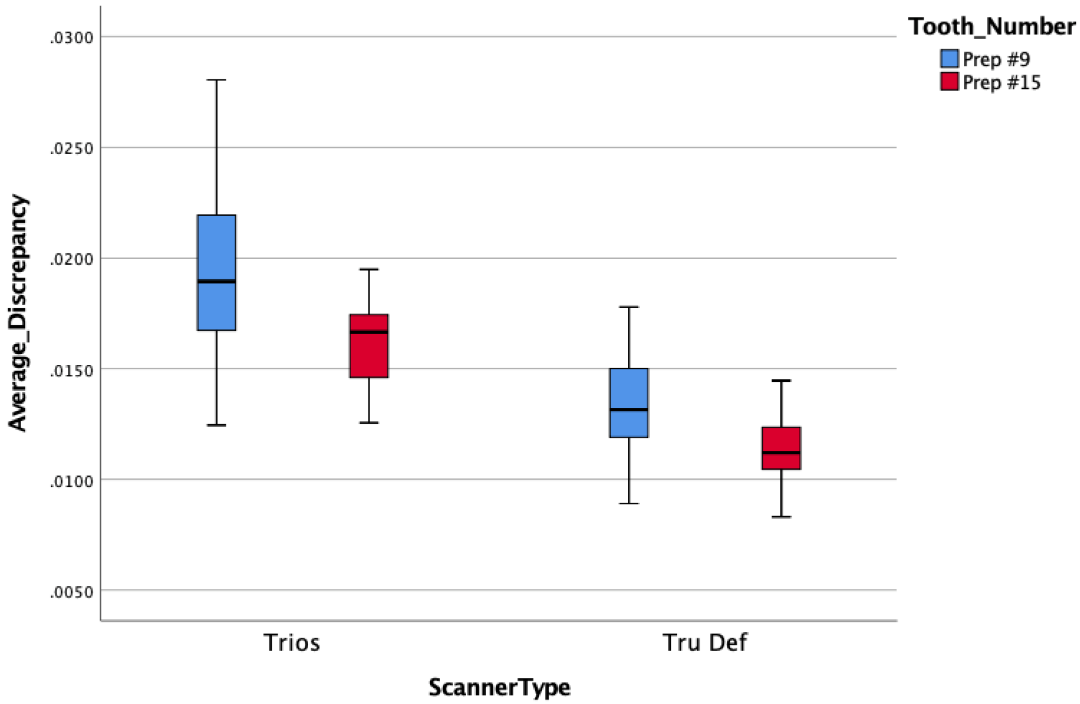

Figure 6. Boxplots showing the difference of accuracy between the two scanners, Trios and Tru Def

Effect of Taper on the Accuracy of the studied intraoral scanners:

The One-way analysis of variance (ANOVA) procedure with Post Hoc analysis was performed for each of the 5 subgroups of the tapers for each scanner and preparation type to determine the significance of difference between the 5 groups. The Tukey honest significant differences test was applied for pairwise comparisons of the groups (a=.05). The diagram below illustrates these comparisons:

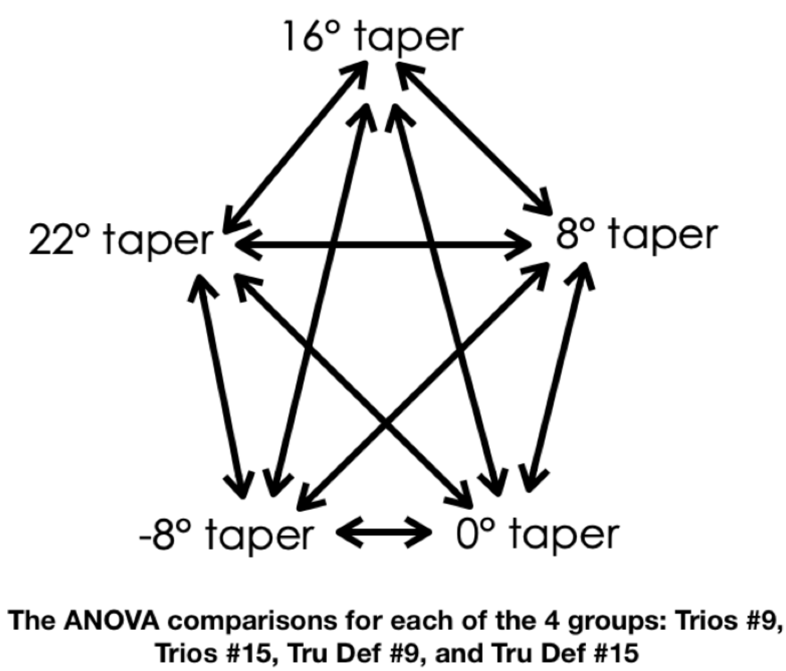

Figure 7. ANOVA comparisons for (-8, 0, 8, 16 and 22 tapers) TOCs of 4 groups (Trios #9, Trios #15, Tru Def #9, Tru Def #15)

Table 5. Tooth discrepancy for Trios preparation #9

TOOTH #9 DISCREPANCY (unit in mm)					
TRIOS	22 degrees (1)	16 degrees (2)	8 degrees (3)	0 degrees (4)	-8 degrees (5)
	0.0136	0.0125	0.018	0.0267	0.0195
	0.0157	0.0181	0.0207	0.0251	0.0207
	0.0126	0.0177	0.018	0.0236	0.0216
	0.0153	0.0184	0.0183	0.0257	0.0207
	0.0153	0.0169	0.0181	0.0281	0.0218
	0.0168	0.0166	0.0211	0.0236	0.022
	0.0142	0.0162	0.0179	0.0257	0.0221
	0.0149	0.0186	0.02	0.0228	0.0182
	0.0133	0.0193	0.0195	0.0244	0.0172
	0.0159	0.0193	0.0197	0.0258	0.0258
Mean (Trueness)	0.01476	0.01736	0.01913	0.02515	0.02096
SD (Precision)	0.001308264	0.002015606	0.001219335	0.001599479	0.002379169
Mean (Trueness) (μm)	14.8	17.4	19.1	25.2	21.0
SD (Precision) (μm)	1.3	2.0	1.2	1.6	2.4

Table 6. Statistical significance between comparisons for TOCs for Trios Preparation #9

TRIOS PREPARATION #9		
Comparison	P-Value	Significance
22° taper VS 16° taper	0.015	Statistically significant
22° taper VS 8° taper	0.000	Statistically significant
22° taper VS 0° taper	0.000	Statistically significant
22° taper VS -8° taper	0.000	Statistically significant
16° taper VS 8° taper	0.187	Not statistically significant
16° taper VS 0° taper	0.000	Statistically significant
16° taper VS -8° taper	0.000	Statistically significant
8° taper VS 0° taper	0.000	Statistically significant
8° taper VS -8° taper	0.149	Not statistically significant
0° taper VS -8° taper	0.000	Statistically significant

Table 7. Average discrepancy between comparisons for TOCs for Trios Preparation #9

Post Hoc Tests

Multiple Comparisons[a]

Dependent Variable: Average_Discrepancy
Tukey HSD

(I) TOC	(J) TOC	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
22 Degrees	16 Degrees	-.0025950*	.0007840	.015	-.004823	-.000367
	8 Degrees	-.0043450*	.0007840	.000	-.006573	-.002117
	0 Degrees	-.0103800*	.0007840	.000	-.012608	-.008152
	-8 Degrees	-.0061850*	.0007840	.000	-.008413	-.003957
16 Degrees	22 Degrees	.0025950*	.0007840	.015	.000367	.004823
	8 Degrees	-.0017500	.0007840	.187	-.003978	.000478
	0 Degrees	-.0077850*	.0007840	.000	-.010013	-.005557
	-8 Degrees	-.0035900*	.0007840	.000	-.005818	-.001362
8 Degrees	22 Degrees	.0043450*	.0007840	.000	.002117	.006573
	16 Degrees	.0017500	.0007840	.187	-.000478	.003978
	0 Degrees	-.0060350*	.0007840	.000	-.008263	-.003807
	-8 Degrees	-.0018400	.0007840	.149	-.004068	.000388
0 Degrees	22 Degrees	.0103800*	.0007840	.000	.008152	.012608
	16 Degrees	.0077850*	.0007840	.000	.005557	.010013
	8 Degrees	.0060350*	.0007840	.000	.003807	.008263
	-8 Degrees	.0041950*	.0007840	.000	.001967	.006423
-8 Degrees	22 Degrees	.0061850*	.0007840	.000	.003957	.008413
	16 Degrees	.0035900*	.0007840	.000	.001362	.005818
	8 Degrees	.0018400	.0007840	.149	-.000388	.004068
	0 Degrees	-.0041950*	.0007840	.000	-.006423	-.001967

*. The mean difference is significant at the 0.05 level.

a. Tooth_Number = Prep #9, ScannerType = Trios

For the Trios tooth preparations of #9, statistically significant differences were observed between all groups except the 16° VS 8° taper and the 8° VS -8° taper. Group 22° was the most accurate and Group 0° was the least accurate. Clinically this was not significant.

Table 8. Tooth discrepancy for Trios preparation #15

TOOTH #15 DISCREPANCY (unit in mm)					
TRIOS	22 degrees (1)	16 degrees (2)	8 degrees (3)	0 degrees (4)	-8 degrees (5)
	0.0131	0.0142	0.017	0.0195	0.0192
	0.0132	0.0158	0.0167	0.0175	0.0184
	0.0136	0.0153	0.0159	0.0171	0.0179
	0.0131	0.0172	0.0171	0.0171	0.0175
	0.0136	0.0164	0.0166	0.0178	0.0178
	0.0145	0.0146	0.0164	0.0171	0.0179
	0.013	0.0149	0.0167	0.018	0.0172
	0.013	0.0151	0.0168	0.0186	0.0172
	0.0126	0.0151	0.0168	0.0166	0.0177
	0.0141	0.0145	0.0166	0.0151	0.0177
Mean (Trueness)	0.01338	0.01531	0.01666	0.01744	0.01785
SD (Precision)	0.000573101	0.000921894	0.000333999	0.001181524	0.000591138
Mean (Trueness) (μm)	13.4	15.3	16.7	17.4	17.9
SD (Precision) (μm)	0.6	0.9	0.3	1.2	0.6

Table 9. Statistical significance between comparisons for TOCs for Trios Preparation #15

TRIOS PREPARATION #15		
Comparison	P-Value	Significance
22° taper VS 16° taper	0.000	Statistically significant
22° taper VS 8° taper	0.000	Statistically significant
22° taper VS 0° taper	0.000	Statistically significant
22° taper VS -8° taper	0.000	Statistically significant
16° taper VS 8° taper	0.000	Statistically significant
16° taper VS 0° taper	0.003	Statistically significant
16° taper VS -8° taper	0.000	Statistically significant
8° taper VS 0° taper	0.177	Not statistically significant
8° taper VS -8° taper	0.011	Statistically significant
0° taper VS -8° taper	0.000	Statistically significant

Table 10. Average discrepancy between comparisons for TOCs for Trios Preparation #15

Post Hoc Tests

Multiple Comparisons[a]

Dependent Variable: Average_Discrepancy
Tukey HSD

(I) TOC	(J) TOC	Mean Difference (I–J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
22 Degrees	16 Degrees	-.0019150*	.0003475	.000	-.002902	-.000928
	8 Degrees	-.0032600*	.0003475	.000	-.004247	-.002273
	0 Degrees	-.0040450*	.0003475	.000	-.005032	-.003058
	-8 Degrees	-.0044550*	.0003475	.000	-.005442	-.003468
16 Degrees	22 Degrees	.0019150*	.0003475	.000	.000928	.002902
	8 Degrees	-.0013450*	.0003475	.003	-.002332	-.000358
	0 Degrees	-.0021300*	.0003475	.000	-.003117	-.001143
	-8 Degrees	-.0025400*	.0003475	.000	-.003527	-.001553
8 Degrees	22 Degrees	.0032600*	.0003475	.000	.002273	.004247
	16 Degrees	.0013450*	.0003475	.003	.000358	.002332
	0 Degrees	-.0007850	.0003475	.177	-.001772	.000202
	-8 Degrees	-.0011950*	.0003475	.011	-.002182	-.000208
0 Degrees	22 Degrees	.0040450*	.0003475	.000	.003058	.005032
	16 Degrees	.0021300*	.0003475	.000	.001143	.003117
	8 Degrees	.0007850	.0003475	.177	-.000202	.001772
	-8 Degrees	-.0004100	.0003475	.763	-.001397	.000577
-8 Degrees	22 Degrees	.0044550*	.0003475	.000	.003468	.005442
	16 Degrees	.0025400*	.0003475	.000	.001553	.003527
	8 Degrees	.0011950*	.0003475	.011	.000208	.002182
	0 Degrees	.0004100	.0003475	.763	-.000577	.001397

*. The mean difference is significant at the 0.05 level.

a. Tooth_Number = Prep #15, ScannerType = Trios

For the Trios tooth preparation of #15, statistically significant differences were observed between all groups except the 8° VS 0° taper groups. Group 22° was the most accurate. Group -8° was the least accurate. There was no clinical significance between the different taper groups.

Table 11. Tooth discrepancy for Tru Def preparation #9

	TOOTH #9 DISCREPANCY (unit in mm)				
TRU DEF	22 degrees (1)	16 degrees (2)	8 degrees (3)	0 degrees (4)	-8 degrees (5)
	0.0134	0.0108	0.0142	0.0129	0.0097
	0.0123	0.0089	0.0126	0.0147	0.013
	0.0101	0.0114	0.0141	0.0154	0.013
	0.0117	0.0116	0.0162	0.0177	0.0119
	0.0096	0.0135	0.0139	0.0165	0.0133
	0.0127	0.0129	0.015	0.017	0.0115
	0.0106	0.0144	0.0131	0.0134	0.016
	0.0119	0.0132	0.0158	0.0178	0.0146
	0.0119	0.0132	0.0152	0.0165	0.0118
	0.0136	0.0124	0.0155	0.0166	0.012
Mean (Trueness)	0.01178	0.01223	0.01456	0.01585	0.01268
SD (Precision)	0.001335665	0.001595166	0.001176813	0.001705709	0.001745343
Mean (Trueness) (μm)	11.8	12.2	14.6	15.9	12.7
SD (Precision) (μm)	1.3	1.6	1.2	1.7	1.7

Table 12. Statistical significance between comparisons for TOCs for Tru Def Preparation #9

Tru Def PREPARATION #9		
Comparison	P-Value	Significance
22° taper VS 16° taper	0.958	Not statistically significant
22° taper VS 8° taper	0.002	Statistically significant
22° taper VS 0° taper	0.000	Statistically significant
22° taper VS -8° taper	0.668	Not statistically significant
16° taper VS 8° taper	0.012	Statistically significant
16° taper VS 0° taper	0.000	Statistically significant
16° taper VS -8° taper	0.965	Not statistically significant
8° taper VS 0° taper	0.337	Not statistically significant
8° taper VS -8° taper	0.061	Not statistically significant
0° taper VS -8° taper	0.000	Statistically significant

Table 13. Average discrepancy between comparisons for TOCs for Tru Def Preparation #9

Multiple Comparisons[a]

Dependent Variable: Average_Discrepancy
Tukey HSD

(I) TOC	(J) TOC	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
22 Degrees	16 Degrees	-.0004700	.0006825	.958	-.002409	.001469
	8 Degrees	-.0027950*	.0006825	.002	-.004734	-.000856
	0 Degrees	-.0040850*	.0006825	.000	-.006024	-.002146
	-8 Degrees	-.0009150	.0006825	.668	-.002854	.001024
16 Degrees	22 Degrees	.0004700	.0006825	.958	-.001469	.002409
	8 Degrees	-.0023250*	.0006825	.012	-.004264	-.000386
	0 Degrees	-.0036150*	.0006825	.000	-.005554	-.001676
	-8 Degrees	-.0004450	.0006825	.965	-.002384	.001494
8 Degrees	22 Degrees	.0027950*	.0006825	.002	.000856	.004734
	16 Degrees	.0023250*	.0006825	.012	.000386	.004264
	0 Degrees	-.0012900	.0006825	.337	-.003229	.000649
	-8 Degrees	.0018800	.0006825	.061	-.000059	.003819
0 Degrees	22 Degrees	.0040850*	.0006825	.000	.002146	.006024
	16 Degrees	.0036150*	.0006825	.000	.001676	.005554
	8 Degrees	.0012900	.0006825	.337	-.000649	.003229
	-8 Degrees	.0031700*	.0006825	.000	.001231	.005109
-8 Degrees	22 Degrees	.0009150	.0006825	.668	-.001024	.002854
	16 Degrees	.0004450	.0006825	.965	-.001494	.002384
	8 Degrees	-.0018800	.0006825	.061	-.003819	.000059
	0 Degrees	-.0031700*	.0006825	.000	-.005109	-.001231

*. The mean difference is significant at the 0.05 level.

a. Tooth_Number = Prep #9, ScannerType = Tru Def

For the Tru Def Preparation of #9, statistically significant differences were observed between groups 22° VS 8° taper, 22° VS 0° taper, 16 VS 8 taper, 16 VS 0 taper, and 0 VS -8 taper. Group 22° was the most accurate. Group 0° was the least accurate. Clinically this was not significant.

Table 14. Tooth discrepancy for Tru Def preparation #15

	TOOTH #15 DISCREPANCY (unit in mm)				
TRU DEF	22 degrees (1)	16 degrees (2)	8 degrees (3)	0 degrees (4)	-8 degrees (5)
	0.0083	0.01	0.0101	0.0086	0.0124
	0.0105	0.0093	0.0128	0.0113	0.0123
	0.0099	0.0101	0.0102	0.0098	0.0124
	0.0109	0.0118	0.0114	0.0121	0.0145
	0.0114	0.0105	0.0112	0.0112	0.011
	0.0097	0.0118	0.0125	0.0132	0.0124
	0.011	0.01	0.0098	0.0122	0.013
	0.0105	0.0113	0.0108	0.0135	0.0125
	0.0113	0.0112	0.0121	0.0109	0.0108
	0.0112	0.0125	0.0106	0.0134	0.0131
Mean (Trueness)	0.01047	0.01085	0.01115	0.01162	0.01244
SD (Precision)	0.000953415	0.001021165	0.001041633	0.001598471	0.001042646
Mean (Trueness) (μm)	10.5	10.9	11.2	11.6	12.4
SD (Precision) (μm)	1.0	1.0	1.0	1.6	1.0

Table 15. Statistical significance between comparisons for TOCs for Tru Def Preparation #15

Tru Def PREPARATION #15		
Comparison	P-Value	Significance
22° taper VS 16° taper	0.950	Not statistically significant
22° taper VS 8° taper	0.679	Not statistically significant
22° taper VS 0° taper	0.191	Not statistically significant
22° taper VS -8° taper	0.004	Statistically significant
16° taper VS 8° taper	0.975	Not statistically significant
16° taper VS 0° taper	0.570	Not statistically significant
16° taper VS -8° taper	0.896	Not statistically significant
8° taper VS 0° taper	0.337	Not statistically significant
8° taper VS -8° taper	0.111	Not statistically significant
0° taper VS -8° taper	0.509	Not statistically significant

Table 16. Average discrepancy between comparisons for TOCs for Tru Def Preparation #9

Post Hoc Tests

Multiple Comparisons[a]

Dependent Variable: Average_Discrepancy
Tukey HSD

(I) TOC	(J) TOC	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
22 Degrees	16 Degrees	-.0003750	.0005178	.950	-.001846	.001096
	8 Degrees	-.0006850	.0005178	.679	-.002156	.000786
	0 Degrees	-.0011500	.0005178	.191	-.002621	.000321
	-8 Degrees	-.0019750*	.0005178	.004	-.003446	-.000504
16 Degrees	22 Degrees	.0003750	.0005178	.950	-.001096	.001846
	8 Degrees	-.0003100	.0005178	.975	-.001781	.001161
	0 Degrees	-.0007750	.0005178	.570	-.002246	.000696
	-8 Degrees	-.0016000*	.0005178	.027	-.003071	-.000129
8 Degrees	22 Degrees	.0006850	.0005178	.679	-.000786	.002156
	16 Degrees	.0003100	.0005178	.975	-.001161	.001781
	0 Degrees	-.0004650	.0005178	.896	-.001936	.001006
	-8 Degrees	-.0012900	.0005178	.111	-.002761	.000181
0 Degrees	22 Degrees	.0011500	.0005178	.191	-.000321	.002621
	16 Degrees	.0007750	.0005178	.570	-.000696	.002246
	8 Degrees	.0004650	.0005178	.896	-.001006	.001936
	-8 Degrees	-.0008250	.0005178	.509	-.002296	.000646
-8 Degrees	22 Degrees	.0019750*	.0005178	.004	.000504	.003446
	16 Degrees	.0016000*	.0005178	.027	.000129	.003071
	8 Degrees	.0012900	.0005178	.111	-.000181	.002761
	0 Degrees	.0008250	.0005178	.509	-.000646	.002296

*. The mean difference is significant at the 0.05 level.

a. Tooth_Number = Prep #15, ScannerType = Tru Def

For the Tru Def Preparation of tooth #15, statistically significant differences were observed only between groups 22° VS -8° taper. Group 22° was the most accurate and Group -8° was the least accurate. There was no clinical significance seen between the different taper groups for the Tru Def tooth #15.

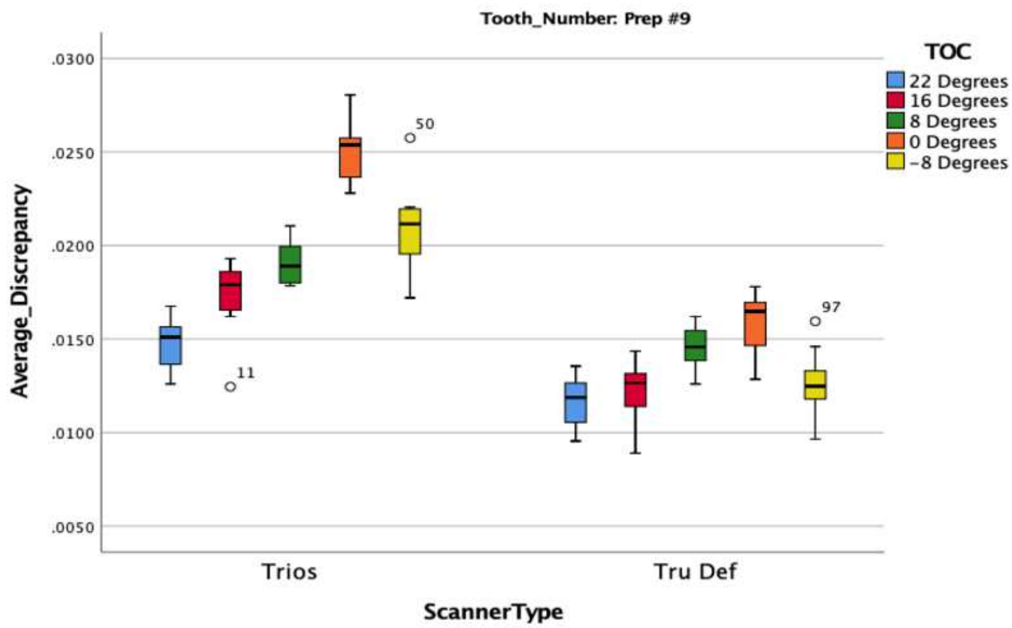

Figure 8. Boxplot of tooth #9 Discrepancy

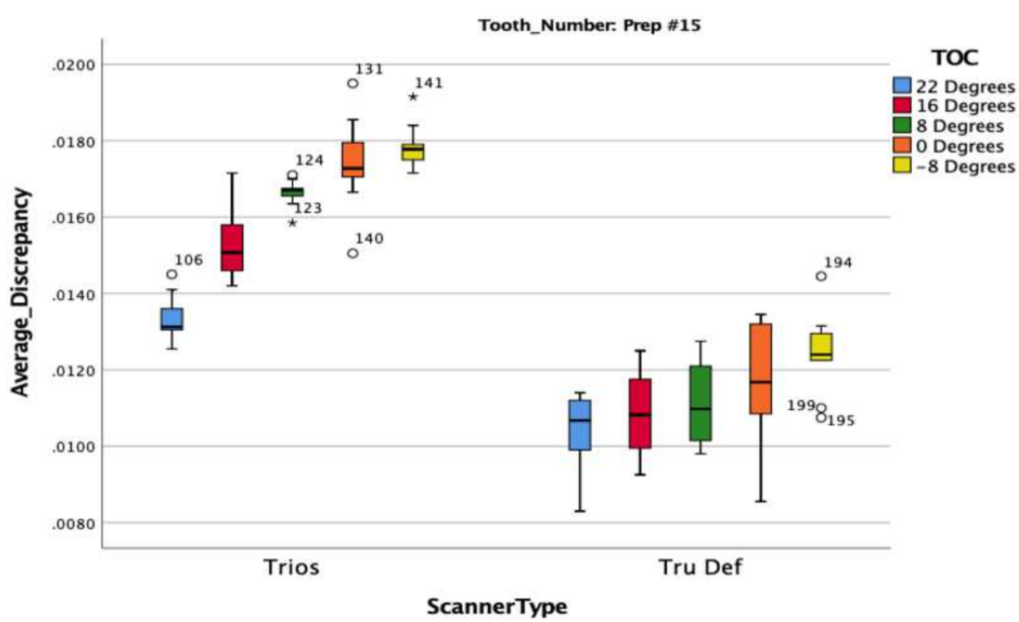

Figure 9. Boxplot of tooth #15 Discrepancy

CHAPTER FOUR

Discussion

On the basis of the results presented in this vitro study, the statement of the null hypothesis that there would be no significant difference in the accuracy of the Trios 3Shape intraoral scanner compared to the True Definition intraoral scanner in regards to arch location and TOC angles was rejected.

The True Definition intraoral scanner demonstrated better performance in regards to the accuracy compared to the Trios 3Shape intraoral scanner which was also seen in Ammoun et al's study in the full coverage crown groups.[17] However, it is worth mentioning that the span evaluated was very small. This discrepancy is on the tooth level and not arch level. It was not in the scope of the study to evaluate the performance of both scanners for longer span restorations.

Undercuts are avoided during crown preparations, however, since it is possible to have undercuts in preparations, the purpose of this study was to evaluate the accuracy of the intraoral scanners when scanning different total occlusal convergences. In regards to comparing total occlusal convergence angles, the accuracy was affected when total occlusal convergence angles were closest to 0 degrees for the complete coverage crown preparations. This is in agreement with results of previously published studies by Mejía et al who reported that impressions made by the polyvinyl siloxane group were significantly less accurate than those made with intraoral scanners.[11]

Figure 8 & 9 exhibits tooth discrepancy in relation to TOC. The box plots seen in these figures demonstrate that as the taper decreases, precision and trueness decreases. Consequently, as taper increases, so does accuracy. One exception to this was that both scanners had the worst accuracy for the parallel preparation for tooth #9. Although the current study's results demonstrated that there was no significant difference in the accuracy of both intraoral scanners in terms of arch location, the anterior preparations were less accurately read by the intraoral scanner. This could be due to the scanners not being able to perform well with preparations that are long and parallel possibly due to the fact that the buccal-lingual distance is minimal. This was also reported in Rudolph et al's study that demonstrated some of the limitations with CAD/CAM Technology.[15] This study showed that long and parallel incisor surfaces were harder to capture when performing a digital scan.

Undercut preparations demonstrated to be the least accurate for the posterior preparations, which could be due to the higher buccal-lingual distance. Although the decrease in taper indicated a decrease of accuracy for the intraoral scanners, it was not significant because 100-120 µm represents the standard clinical level of significance used at the fabrication level[18,19] and the clinical meaningful amount of error was set at 50 µm. The reason 50 µm was chosen as the threshold of significance was due to the fact that average scanning discrepancy from previous studies on the tooth levels varied between 20 and 40 µm. We also gave an additional 10 µm to allow for the discrepancy that could possibly have resulted from the desktop scanning. Based on the previous literature regarding the discrepancy from scanning and fabrication, and based on the numbers we obtained in our study, the maximum clinical acceptable discrepancy that can be obtained from data acquisition and scanning should be 50 μm. We also decided to go with a reduced tolerance parameter to test the limits to which the scanners are capable of scanning accurate information. Although the tolerance was set to 50 μm, even if it was set at 100 μm it would not have demonstrated clinical significance because there was no clinical significance seen at 50 μm.

Limitations of this study include 14 μm of printing error for SLA technology[14] and only two intraoral scanners were utilized. Our study indicates that the clinician should be aware of the limitation of the intraoral scanners with regards to scanning teeth preparations with adjacent teeth, certain preparation TOCs and heights and should consider alternate impression techniques.

CHAPTER FIVE

Conclusion

Within the limitations of this in vitro study, the following conclusions can be drawn:

1. The Tru Def Scanner revealed more accuracy compared to the Trios scanner for all variables under the conditions in this study.
2. Anterior preparations were less accurately read by the scanners than for the posterior preparations.
3. Parallel preparations were the least accurate for the anterior teeth and undercut preparations were the least accurate for the posteriors.
4. Overall, the decrease in taper decreased the accuracy of intraoral scanners, however, this was not clinically significant. Further clinical studies need to be carried out to confirm the findings of this study.

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