Comparison between direct, virtual aided by clinician and artificial intelligence bonding techniques in Orthodontics

by

Johana Ivelisse Cortés-Mercado, D.M.D.

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Thesis Advisor: Tarek ElShebiny B.D.S., M.S.D.

Committee Members:

Juan Martin Palomo D.D.S., M.S.D.

Neda Stefanovic D.D.S, MSc, Ph.D.

Case Western Reserve University

School of Dental Medicine

Department of Orthodontics

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DEDICATION

I dedicate this thesis to my loving mother Johana, and my dear brother Jesus Abdiel. Thanks are not enough for your unconditional love and support. To my loving grandparents, Yaya, Yoyo, César and Lucy, who encouraged me to always dream big and to work hard to achieve my goals. Thank you for always being there for me.

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Abstract

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Introduction: Bracket positioning is one of the most critical stages of orthodontic treatment. That is why advantages and disadvantages between direct and indirect bonding techniques have been discussed constantly in the orthodontic world. The purpose of this study is to determine if they are any significant differences between direct, virtual, and artificial intelligence bonding techniques in any of the 3 dimensions of space.

Methods: In this study, 14 patients who started orthodontic treatment with full fixed appliances at a private practice in Parma, Ohio. All subjects were in permanent dentition. Patients with abnormal tooth morphology, restoration(s) that altered natural morphological integrity of the crown, poor oral hygiene, craniofacial anomalies, or syndromes were excluded.

The sample size calculation and all the statistical analyses were performed in SPSS 22.0 (IBM, Armonk, NY, USA). All statistical tests were assessed at the 0.05 significance level. Our sample size calculation showed that at least 14 dental arches would be needed for each group to detect a minimum RMS clinical difference of 0.50mm (Palone et al) and a standard deviation of 0.22mm with a power of 80% and a significance level of 0.05.

A digital intraoral scan (IO scan) for each subject was taken at the initial records appointment. Another digital IO scan was taken after direct bonding. IO scanner used in our study was the iTero Element 2 scanner (Align Technologies, San Jose, Calif). The digital scan taken prior to direct bonding was submitted to Dibs AI software to digitally place brackets. Each initial IO scan was submitted twice; one to evaluate the AI bracket placement and a second time for a virtual setup with clinician modifications. Brackets use for this study in-vivo and virtually were 3M Victory Low Profile MBT slot .022 slot (3M Unitek, Monrovia, Calif)

None of the virtual bonding setups were used intraorally with the patient. Therefore, having 2 out of the 3 study variables up to this point: virtual bracket placement aided by AI and virtual bracket placement

aided by the clinician. The third variable is the IO scan taken after direct bonding in-vivo. (Figures 1 &2)

After having the 3 variables stereolitography (.stl) files (direct bonding, AI and clinician) we segmented the arches into individual teeth units using the sculpting tool from Dolphin Imaging Software (Figure 3) Then Geomagic (3D mesh processing software) was utilized to superimpose the individual segmentations to assess bracket placement differences using the direct bonding IO scan as reference. Best fit superimpositions were performed using Geomagic® Control X, data was collected as both numerical values and color-coded deviation maps. (Figures 4&5)

Descriptive statistics were computed, and statistical significance was set at $p<0.05$. A Shapiro Wilk test was performed, and we found our data was not normally distributed. (Table 1) Therefore Kruskal-Wallis test was conducted between groups to assess for statistically significant differences in changes to the bracket positioning. (Tables 2&3) Post-hoc test for multiple comparisons was performed between groups for parameters showing significant differences. (Tables 6-25)

Results: A total of 840 teeth (central incisors to second premolars) were evaluated. The intraclass correlation coefficient test showed good correlation (0.894). For this study we were studying 2 variables: A) the differences in bracket positioning between the direct bonding method (DB) and the virtual bonding done by artificial intelligence (AI) & B) differences in bracket positioning between the direct bonding method (DB) and the virtual bonding done by the clinician (Clin). All the statistical analyses were performed with SPSS 22.0 (IBM, Armonk, NY, USA). A Shapiro-Wilks test was performed to assess our data normality distribution of found our data is not normally distributed. Nonparametric testing was performed to evaluate our data. (Table 1)

Group A: Direct Bonding vs AI

The Kruskal-Wallis comparison test showed a statistically significant difference between all the values; RMS (root mean square), minimum and maximum values with a p-value of <0.05 (Table 2).

Descriptive statistics on table 4 show 4 values with clinically significant differences in this group (>0.50mm). Mandibular lateral incisors (0.60mm), maxillary lateral incisors (0.56mm), maxillary second premolars (0.54mm) and maxillary first premolars (0.53mm).

A post-hoc Tukey test for multiple comparisons revealed significant differences between maxillary lateral incisors & maxillary second premolar bracket positioning when compared to the rest of the teeth units ($p<0.05$) (Tables 7&10) Also, statistically significant differences were found between mandibular lateral incisors when compared to the rest of the teeth <0.05. (Table 12) The teeth with the least number of differences within the groups were the maxillary central incisors and the mandibular second premolars. (Tables 6&15)

Group B: DB vs. Clinician

The Kruskal-Wallis comparison test showed a statistically significant difference between all the values; RMS (root mean square), minimum and maximum values with a p-value of <0.05 (Table 3).

Descriptive statistics on table 5 show 3 values with clinically significant differences in this group (>0.50mm). Maxillary second premolars (0.54mm) and maxillary first premolars (0.52mm) and mandibular second premolars (0.51mm)

A post-hoc Tukey test for multiple comparisons revealed significant differences between maxillary second and first premolars

when compared to the rest of the teeth units ($p<0.05$) (Tables 19&20) Also, statistically significant differences were found between mandibular second premolars when compared to the rest of the teeth <0.05. (Table 25) The teeth with the least number of differences within the groups was the mandibular lateral incisors. (Table 22)

There were more discrepancies in Group A (DB vs AI) with 4 values over 0.50mm when compared to Group B (DB vs Clin) that only had 3 values over that threshold. On Group A the teeth with the highest discrepancy were the mandibular & maxillary lateral incisor, while in Group B the teeth with the most discrepancy were the maxillary second and first premolar.

Conclusion: The aim of this study was to find if there were any significant or clinical differences between direct bonding (jn-vivo), virtual bonding aided by clinician and artificial intelligence bonding techniques. We rejected the null hypothesis and accepted the alternative hypothesis.

We found statistically and clinically significant differences between AI and Clinician when compared to direct bonding. With our data, we could infer that if we were to compare AI Vs Clinician, there

might not be any clinically significant differences since the differences between this fall below 0.25mm. (Tables 4&5). To our best knowledge this study is first of its kind, since in-vivo conditions are much more complex and unpredictable than in vitro experiments and will hopefully bring some more insight and knowledge to this emerging field of research.

Review of Literature

Indirect Bonding

Bracket positioning is one of the most critical stages of orthodontic treatment. Imprecision in bracket location may lead to undesired tooth movement like rotations, unplanned torque, and vertical changes. There are two main techniques of bracket placement, direct and indirect. Advantages and disadvantages between both bonding techniques have been discussed constantly in the orthodontic world. The most often used technique, direct bonding, undoubtedly carries some disadvantages like, long bonding time, need for wire bending in later stages of treatment, bracket repositioning and bracket positioning inaccuracies. [1]

Direct bonding is believed to take more clinical chair time, therefore adding more stress factor to the orthodontist. With indirect bonding appliance position is previously planned and then transferred into the oral cavity. Indirect bonding is a precise and time-saving method of bracket placement, growing in popularity in recent years. Even though it has been advocated for many years, as early as 1970's, to improve efficiency and outcome of treatment, this technique is still

only being used by a minority of orthodontists.[2] Is important to mention that indirect bonding is far more technique sensitive and requires more laboratory procedures and time besides chair time.[3]

More than 50 years ago, Silverman and Cohen revolutionized orthodontics as we know it with this technique. They develop the idea from placing fixed appliances on a cast model in the desirable location within each tooth.[4] Then they use a vacuum formed tray as a transfer medium. More research was developed in that area to improve the effectiveness of indirect bonding. In 1999, Sondhi, introduced to the orthodontic world an indirect bonding system designed for extraoral bracket placement thanks to the further development of curing adhesives.[5] Accuracy of indirect bonding systems have been widely discussed in the literature. In addition to the accuracy, reduced chair time, replication, and lower risk of saliva contamination are considered advantages of indirect bonding when compared to the direct bonding techniques.[6]

Indirect bonding undergoes constant evolution and innovation. Before digital workflows were introduced into the IDBS (indirect bracket bonding system), all the steps were performed manually, which was

extremely time-consuming. Thanks to the advances in technology digital software's were created to allow for precise bracket placement with reduced lab time. After virtual placement of the brackets on the digital software, transferring them to the exact locations where the brackets are intended to be placed on the patient intraorally is of vital importance. Different transfer tools have been used and studied through the years. Initially we started with vacuum formed materials which are simple to make but its characteristic flexibility makes it prone to deformation and therefore may also affect accuracy.[7] In 2014, after experimenting with the use of silicone materials with the indirect bonding technique, Castilla et al. suggested that the accuracy of the bracket position of both silicone and thermoformed tray were similar, but the consistency of the bracket position was higher with the silicone tray.[8]

More recently, computer-aided design/computer- aided manufacturing (CAD/CAM) transfer trays have been introduced to our field, and studies of its accuracy have been and continue to be conducted. It was suggested that the CAD/CAM transfer tray shows clinically acceptable results when compared to a silicone tray.[9] Xue et al. also studied the accuracy of a new bracket transfer design device

using CAD/CAM technology. With exception of some torque deviation measurements, most of the measurements were within the clinically acceptable range.[10]

Earlier this year, Palone et al. found in their study that medium-soft, transparent CAD-CAM transfer trays enable accurate linear and angular in-vivo transfer of brackets. No directional bias was found, indicating that soft transparent CAD-CAM transfer trays may provide a good fit and stability during clinical procedures.[11]

Digital Orthodontics

Digital technologies in the orthodontic field are used in a wide array of functions like intraoral scanning, 3D printing, bracket and aligners design, improved treatment planning, surgical planning, virtual bracket removal, just to name a few. For digital orthodontics to be successful it's important to have a well implemented workflow that includes digital file acquisition for the purpose of viewing, editing, and printing of digital files. While many orthodontic practices and academia have been using digital technologies for decades now,[12] committing to

a fully digital practice may bring many challenges since it requires proper professional training and financial investments.[13]

The use of digital technology for indirect bonding has become very popular the last decade.

Intraoral scanning

Thanks to the advances and innovations on digital dentistry, the current and future generations of orthodontists will remember the alginate impressions as something to be found on display at a Museum of Dental History. It is fair to say that intraoral digital scanners have and will continue to revolutionize our profession, but not without some resistance. Although some of us are training fully or almost fully digital, the same is not true for some residency programs and the same applies for clinics and offices. Intraoral digital scanners have become an essential tool for the modern orthodontic office. Some benefits of using intraoral digital scanning technology are that is more tolerable for patients, faster, easily transferable, cleaner, and even more accurate. Therefore, improving patient experience and practice efficiency when compared to analog dental impressions (alginate, polyvinyl siloxane).[14] Analog impressions have been associated with problems such as tears, voids, tray to tooth contact, bubbles, limited working time, breakage

upon removal, size distortion of material, inaccurate pouring, breakage of cast, among many more. But the worst complication from analog impressions is the anxiety and discomfort caused to patients with sensitive gag reflexes. In vitro studies have widely demonstrated that full-arch digital intraoral scans are as accurate as analog impressions, without these inconveniences.[15]

From the clinician standpoint, advantages of digital scanning include improved and faster diagnosis and treatment planning, decreased retakes and chair time, minimization of storage requirements, faster records submission to laboratories and insurance providers, standardization of office procedures, enhanced workflow, improved appliance accuracy and lower inventory expense. Some benefits for patients besides more comfort include reduced chair time, improved case presentations, and easier and quicker fabrication of lost or broken appliances, as well as potentially reduced treatment time.[14]

Intraoral scanners work their magic by collecting surface data points of both soft and hard dental tissues for study, diagnosis, measurement, manipulation, treatment prediction & electronic storage of pre-, intra- and/or post-treatment information.

In 1985, tridimensional scanning in dentistry was launched by Dentsply Sirona with the release of their chairside economical restoration of esthetic ceramics (CEREC) intraoral scanner. The goal of the CEREC was to capture digital 'impressions' for fixed prosthetic restorations, within the scope of prosthodontists and general dentists.[16] But in 1999 this technology was finally introduced to the orthodontic community by Orthocad, who scanned orthodontic casts at their company headquarters in Poland for digital study/analysis.[17] It was not until 2006 that chairside intraoral scanning was introduced in university and private practice orthodontic settings when the iTero (Align Technologies, San Jose, California) digital impression scanner was released. At that time, the integration for this technology was not attainable for most of the clinicians mainly due to the exorbitant price tag. 17 years later, is fascinating to see the number of companies that now offer intraoral digital scanners; each presenting slightly different features, to some extent, to be able hold stake in the current marketplace. Features like initial cost, monthly service and maintenance fees, weight, size, portability, speed, data storage, screen size/functionality, user experience, sensor response, auxiliary features (outcome simulator, caries detection) and others, are some of the factors clinicians take into consideration before purchasing an intraoral digital scanner. But

regardless of the brand, all three-dimensional intraoral scanners are fabricated with these three major components: a mobile workstation that support data entry, a handheld camera wand to collect data and a monitor.[14]

Collection of data methods varies by scanner; regardless of if it is via laser or white light, the goal is to collect hundreds of thousands of measurements per inch and to replicate the original object as a 3D representation. The different types of technology methods used with intraoral scanners camera wands are near infrared imaging (NIRI), accordion fringe interferometry (AFI), triangulation, parallel confocal and three-dimensional in-motion video. The iTero element 2 uses parallel confocal imaging, which utilizes focused red and white laser light to tomographically slice object data and stitch it back together to create a final picture. This technology is often referred to as 'point-and-stitch reconstruction'.[18]

The precision, reliability, and accuracy of digital intraoral scanning as an acceptable alternative to analog impression taking, has been widely studied since the technology's introduction to the orthodontics field.[19–21] Digital scans taken with orthodontic fixed appliances in place,

have shown slight discrepancies, however all results were considered clinically acceptable, with 3D superimposition comparison. It has also been proven that he presence or absence of fixed appliances did not affect the overall dimensions of the scanned teeth at the level of the occlusal surface.[22] But it is important to take into consideration that this technology is technique sensitive and requires certain level of skills and operator experience to be able to capture accurate and precise digital scans regardless of the presence or absence of orthodontic appliances.

The most significant driving force towards the complete transition from analog to digital impressions has been patient satisfaction. In 2015 a study that investigated patient perception of burdens during dental treatment highlighted that patients' reported traditional impressions 'unpleasant and burdensome'.[23] Furthermore, patients also reported they would prefer to seek treatment from practitioners who use digital impressions over those who take alginate impressions. When comparing brands of intraoral digital scanners, a satisfaction questionnaire taken by patients in orthodontic treatment reported that intraoral scans taken with an iTero scanner were significantly more comfortable, patient's experienced less pain and dry mouth, than with TRIOS (3Shape, Copenhagen, Denmark) scanner or alginate impressions.[24]

Artificial intelligence

Although it is a very popular and consistently mentioned term now a days, 'artificial intelligence' was actually proposed by Dr. Johnathan McCarthy, almost 70 years ago, in 1955, in a summer research project at Dartmouth College in Hanover, New Hampshire. With this project the authors were attempting to 'find out how to make machines use language, form abstractions and concepts, solve kinds of problems now reserved for humans and improve themselves'.[25]

Artificial Intelligence is defined as: 'the theory and development of computer systems able to perform tasks that normally require human intelligence' by the Oxford English Dictionary. In simpler terms, artificial intelligence is the field of science in charge of creating machines or computer systems capable of performing tasks that historically were only humanly possible, such as decision making, problem solving and reasoning. In 2017, Hamet & Tremblay described Artificial intelligence (AI) as a "system's ability to mimic human-like intelligence or be defined as making effective and right decisions according to a gold standard". The key aspects of artificial intelligence are machine learning, neural networks, deep learning, and artificial intelligence itself.[26]

The most essential part of artificial intelligence (AI) is machine learning. Machine learning uses algorithms to make predictions based on data sets collected from a myriad of research disciplines. Machine learning then analyzes data and creates a neural network that mimics the human brain. An established neural network can be used then for deep learning, which is utilized for automatic pattern recognition and improvement of future detection.[27,28]

The integration of AI within Dentistry has the solely purpose of bringing accuracy, precision, and efficiency to our profession. In our orthodontics field, AI has been used for treatment predictions, automatic anatomy detection, cephalometric analysis and landmark identification, tooth segmentation, determining need for orthodontic extractions, measuring the degree of maturation of the cervical vertebra, predicting the facial and soft tissue changes after orthognathic surgery, monitoring treatment and more. These systems have proven to be very efficient in performing the tasks for which they have been designed.[27]

In 2010 a study by Xie investigated the accuracy of AI by determining if an extraction vs a non-extraction treatment plan would be most beneficial to reduce or eliminate dental malocclusions, by using lateral cephalometric images (data points of anterior teeth uncovered by incompetent lips and IMPA). The study concluded that AI was able to diagnose, with 80% accuracy, whether malocclusions in patients 11-15 years of age 'required' extractions.[29,30] Another study, published in 2016 by Jung et al., investigated the implementation of decision tree as well, for AI to diagnose the need for extractions using multiple extraction patterns. The authors concluded that there was a 93% success rate for AI diagnosis extraction vs non-extraction and 84% for specific extraction pattern.[31]

In 2021, a systematic review by Monill-Gonzáles et al, concluded that AI in the orthodontics field might be very useful for time consuming or high precision procedures, and most valuable to decrease observer errors. The authors also emphasize that AI is just another tool and any final health decisions will always be the clinicians' responsibility.[32] As recent as this year, Strunga et. al scoping review identified several limitations of AI-powered systems in Orthodontics. The authors highlight that even though AI can be very helpful with diagnosis and treatment planning me must understand AI is not as accurate as a trained

orthodontist in identifying and treating complex cases. They also mention that AI systems lack the same level of clinical expertise as a trained orthodontist. AI may not be capable to fully understand the patient's needs and complaints and cannot provide the same level of individualized care as a doctor would. Cost is another limitation the authors talk about since AI systems can be very expensive and accessibility to this technology is not possible for everyone. Other limitations mentioned by the authors are regulations and ethical concerns with AI systems.[33]

Dibs AI

There are several commercial lab solutions for indirect bonding in the orthodontic market. One of the most popular and used for our study is OrthoSelect's (American Fork, UT) Digital Indirect Bonding System (DIBS). The company offer two pathways; after secure transfer of the STL files and instructions about bonding heights and bracket system to be used, the company will segment and set-up the case and submit the bracket setup to the doctor for review. Their software will allow the doctor to make modifications of the positioned brackets and after approval the bonding tray can be designed and produced in the lab

and shipped to the doctor or the STL files of the bonding tray sent to the doctor for printing in-house.[2]

Despite the software popularity and establishment almost 20 years ago, published studies or research regarding this product are not available. Claims and information about the DIBS product found at OrthoSelect website were: "Founded in 2004, OrthoSelect is a leader in digital orthodontics with the mission to help orthodontists achieve greater clinical efficiency through state-of-the-art technology and provide improved treatment outcomes for their patients. With proven expertise in both orthodontic software for precision bracket placement and orthodontic laboratory services, the company completes thousands of patient cases monthly in more than a dozen countries. The DIBS AI software platform simplifies and automates the process of orthodontic patient case setups, creates predictive outcomes based on your preferred bracket prescriptions, and provides the flexibility to 3D print extremely accurate bracket transfer appliances (commonly known as IDB trays). These advancements free up precious doctor, staff, and chair time by shortening bonding appointments by a third or more, as well as reducing overall treatment time through significant decreases in wire bending and bracket repositioning. The benefits in improved

accuracy and time savings can result in a reduction of 25% or more of the orthodontist's cost of treatment. our technicians and advanced AI will begin providing customized case setups based on each doctor's individual preferences".[34]

Geomagic Control X

This engineering software created in 1997 by Fu and Edelsbrunner, is now considered the gold-standard for superimpositions and objects comparisons within many disciplines including engineering and dentistry. The initial goal of the creators was to expand custom manufacturing techniques with 3D printers. Some manufacturing examples were prosthetics limbs, shoes, and NASA spaceships repair parts.[35] In the early 2000's the company signed a deal with Align Technologies that allowed for growth and market expansion. With the aid of Geomagic, a 3D CAD/CAM software, we can compare, inspect, and interpret digital scan data.[36] One of the comparison features includes best fit alignment, which supplies information like maximum and mean differences and standard deviation of thousands of data points between digital 3D models.

Another useful feature that the software allows to create is the color mapping tool, which can be used as a visual aid of the data points selected.[37] Geomagic has been widely used in the dental field with specialties like prosthodontics, orthodontics, oral surgery, and restorative dentistry. As an example, a 2021 study by Blundell et al, used Geomagic Control X to assess the discrepancy in overbite expression posttreatment.[38] Another research article, by Palone et al, used Geomagic Control X to measure the accuracy of indirect bracket placement via the soft, transparent CAD-CAM transfer tray on digital superimpositions of the tooth surfaces of the original CAD models with the planned bracket positions and the in-vivo models with actual bracket positions.

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STATEMENT OF THESIS

- **Objective**: The purpose of this study is to determine if they are any significant differences between direct, virtual, and artificial intelligence bonding techniques in any of the 3 dimensions of space.

- **Null Hypothesis:** There is not statistically or clinically significant differences in bracket positioning between direct, virtual, and artificial intelligence bonding techniques.

- **Alternative Hypothesis:** There are statistically or clinically significant differences in bracket positioning between direct, virtual guided by clinician and artificial intelligence bonding techniques.

MANUSCRIPT FOR PUBLICATION

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Comparison between direct, virtual aided by clinician and artificial intelligence bonding techniques in Orthodontics

Authors: Johana Cortés-Mercado, D.M.D[1]

Tarek ElShebiny, B.D.S, M.S.D.[2]

Neda Stefanovic, D.D.S, M.Sc., Ph.D. [3]

Juan Martín Palomo, D.D.S, M.S.D.[4]

1. Resident, Department of Orthodontics, Case Western Reserve University, Cleveland, OH, USA

2. Assistant Professor and Clinic Director, Department of Orthodontics, Case Western Reserve University, Cleveland, OH, USA

3. Assistant Professor, Department of Orthodontics, University of Belgrade, Belgrade, Serbia

4. Professor and Program Director, Department of Orthodontics, Case Western Reserve University, Cleveland, OH, USA

Corresponding author:
Johana Cortes-Mercado
Case Western Reserve University
School of Dental Medicine
Department of Orthodontics
9601 Chester Avenue
Cleveland, OH 44106
jic28@case.edu

Introduction

Bracket positioning is one of the most critical stages of orthodontic treatment.[1,39] That is why advantages and disadvantages between direct and indirect bonding techniques have been discussed constantly in the orthodontic world.[40] The most often used technique, direct bonding, undoubtedly carries some disadvantages like, long bonding time, need for wire bending in later stages of treatment, bracket repositioning and bracket positioning inaccuracies.[1] Direct bonding is believed to take more clinical chair time, therefore adding more stress factor to the orthodontist[41–43]. Even though indirect bonding has been advocated for many years (as early as 1970's) to improve efficiency and outcome of treatment, this technique is still only being used by a minority of orthodontists.[2] Is important to mention that indirect bonding is far more technique sensitive and requires more laboratory procedures and time besides chair time.[3] Technology is drastically changing the ways we live and work. So, if change is inevitable, we might as well embrace it. Digital advances like intra-oral scanning and 3D printing are now so far advanced and more accessible to orthodontists.[2,14] The ability to capture the dentition and the occlusion quickly and precisely with intra-oral scanners is now well known to orthodontists. The accuracy of this

technology is very well documented and acceptable for daily clinical orthodontics.[2]

These digital advances made possible the development of the virtual indirect bonding technique.[44] Nowadays, a variety of software programs offer virtual bracket placement with the aid of artificial intelligence. The purpose of this study is to determine if they are any significant differences between direct, virtual aided by clinician and artificial intelligence bonding techniques in any of the 3 dimensions of space.

Material and Methods

In this study, 14 patients who started orthodontic treatment with full fixed appliances at a private practice in Parma, Ohio. All subjects were in permanent dentition. Patients with abnormal tooth morphology, restoration(s) that altered natural morphological integrity of the crown, poor oral hygiene, craniofacial anomalies, or syndromes were excluded.

The sample size calculation and all the statistical analyses were performed in SPSS 22.0 (IBM, Armonk, NY, USA). All statistical tests were assessed at the 0.05 significance level. Our sample size calculation

showed that at least 14 dental arches would be needed for each group to detect a minimum RMS clinical difference of 0.50mm (Palone et al) and a standard deviation of 0.22mm with a power of 80% and a significance level of 0.05.

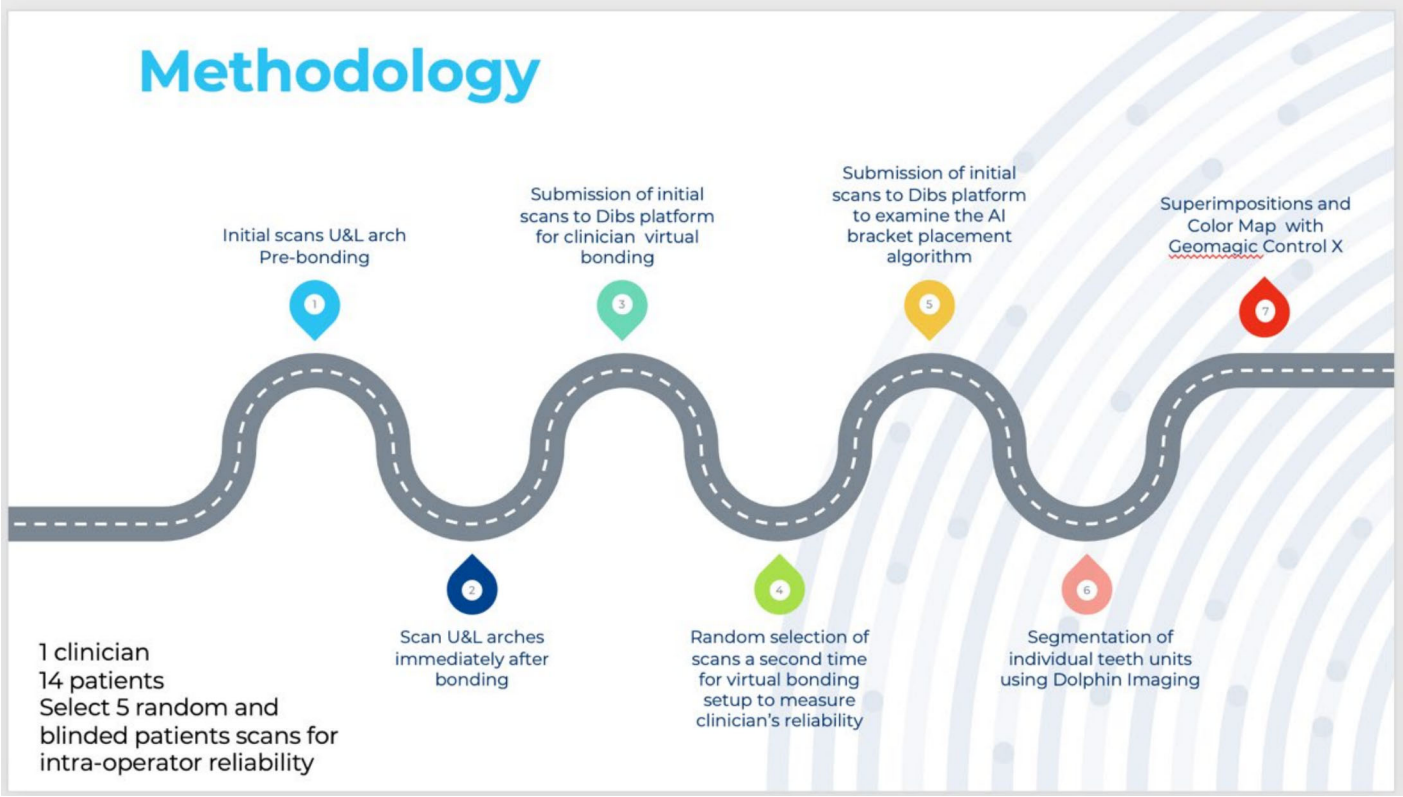


Figure 1: Methodology Road Map

A digital intraoral scan (IO scan) for each subject was taken at the initial records appointment. Another digital IO scan was taken after direct bonding. IO scanner used in our study was the iTero Element 2

scanner (Align Technologies, San Jose, Calif). The digital scan taken prior to direct bonding was submitted to Dibs AI software to digitally place brackets. Each initial IO scan was submitted twice; one to evaluate the AI bracket placement and a second time for a virtual setup with clinician modifications. Brackets use for this study in-vivo and virtually were 3M Victory Low Profile MBT slot .022 slot (3M Unitek, Monrovia, Calif)

None of the virtual bonding setups were used intraorally with the patient. Therefore, having 2 out of the 3 study variables up to this point: virtual bracket placement aided by AI and virtual bracket placement aided by the clinician. The third variable is the IO scan taken after direct bonding in-vivo. (Figures 1 &2)

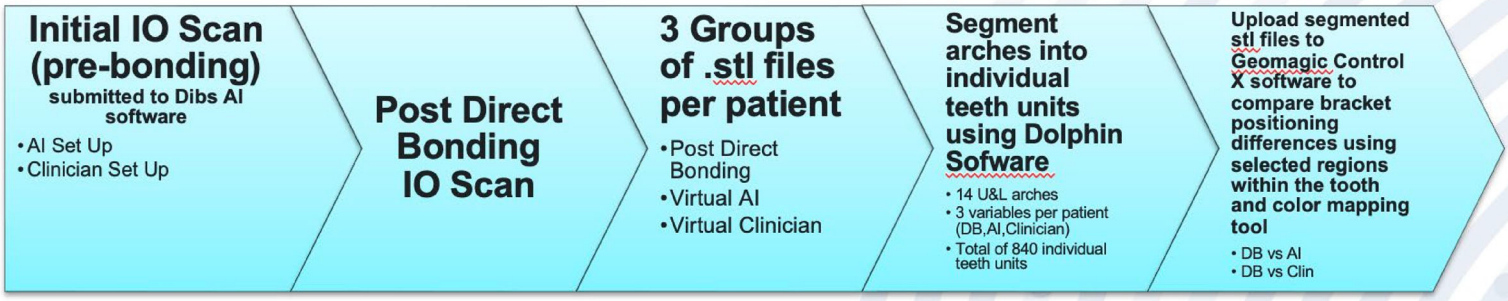


Figure 2: Flowchart of Methodology Steps

After having the 3 variables stereolitography (.stl) files (direct bonding, AI and clinician) we segmented the arches into individual teeth units using the sculpting tool from Dolphin Imaging Software (Figure 3)

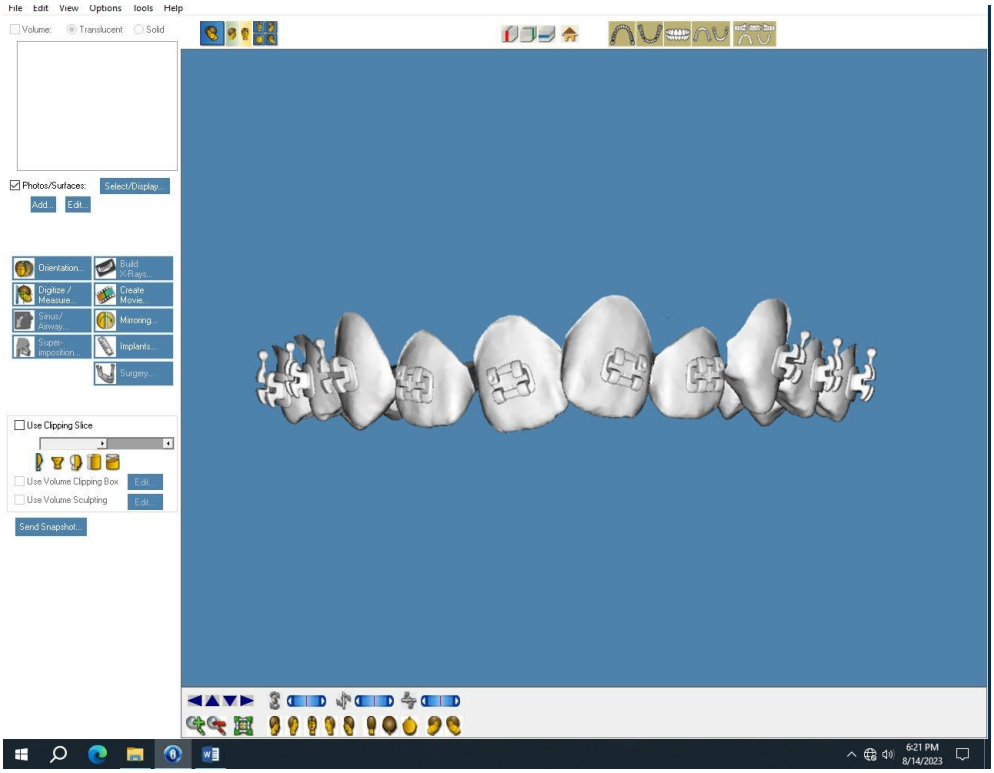


Figure 3: Segmentation process using Dolphin Imaging Software

Then Geomagic (3D mesh processing software) was utilized to superimpose the individual segmentations to assess bracket placement differences using the direct bonding IO scan as reference. Best fit superimpositions were performed using Geomagic® Control X, data was

collected as both numerical values and color-coded deviation maps.

(Figures 4&5)

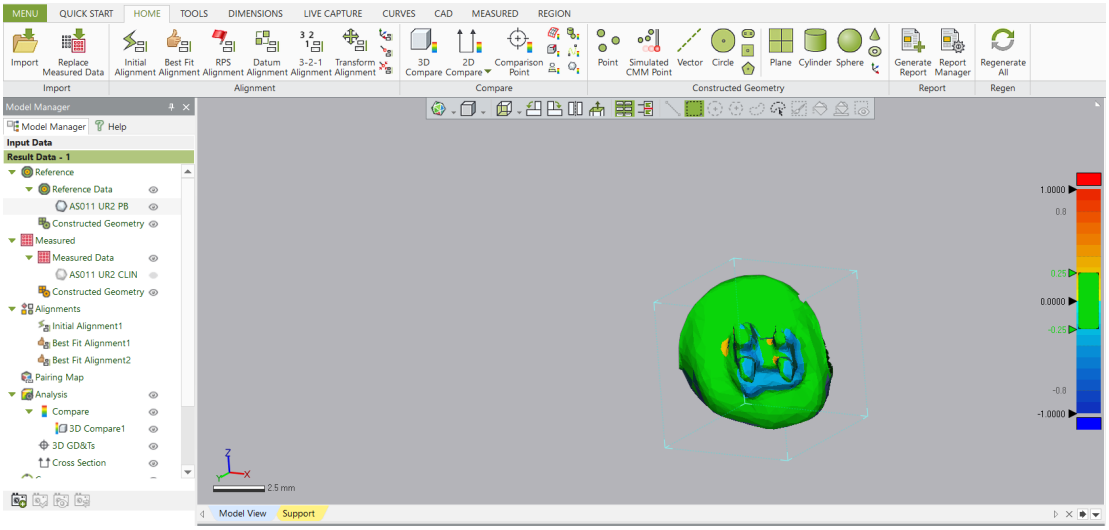


Figure 4: Best fit superimposition and color mapping tool example using Geomagic Control X software between UR2 direct bonding and UR2 clinician virtually modified.

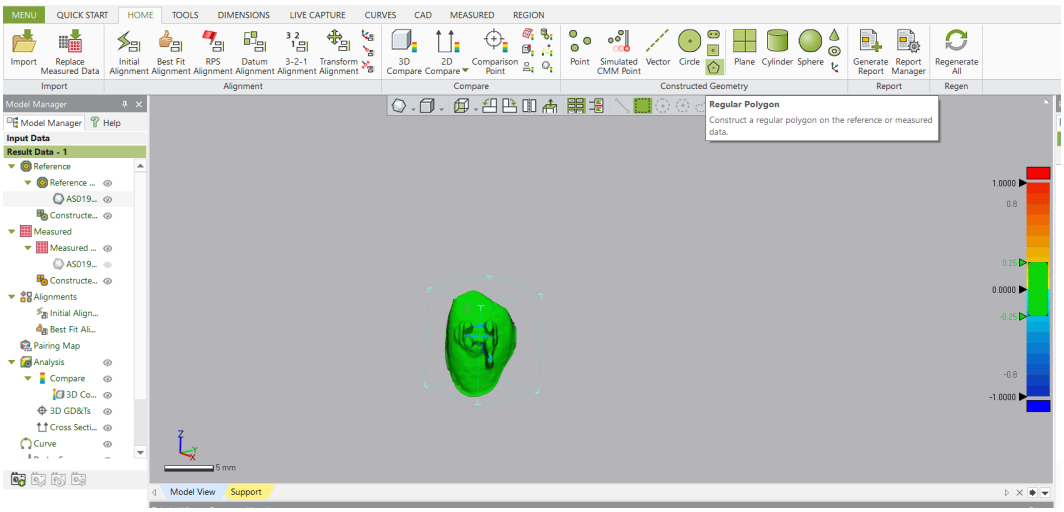


Figure 5: Best fit superimposition and color mapping tool example using Geomagic Control X software between LL3 direct bonding and LL3 AI.

Descriptive statistics were computed, and statistical significance was set at $p<0.05$. A Shapiro Wilk test was performed, and we found our data was not normally distributed. (Table 1) Therefore Kruskal-Wallis test was conducted between groups to assess for statistically significant differences in changes to the bracket positioning. (Tables 2&3) Post-hoc test for multiple comparisons was performed between groups for parameters showing significant differences. (Tables 6-25)

Results

A total of 840 teeth (central incisors to second premolars) were evaluated. The intraclass correlation coefficient test showed good correlation (0.894). For this study we were studying 2 variables: A) the differences in bracket positioning between the direct bonding method (DB) and the virtual bonding done by artificial intelligence (AI) & B) differences in bracket positioning between the direct bonding method (DB) and the virtual bonding done by the clinician (Clin). All the statistical analyses were performed with SPSS 22.0 (IBM, Armonk, NY, USA). A Shapiro-Wilks test was performed to assess our data normality distribution of found our data is not normally distributed. Nonparametric testing was performed to evaluate our data. (Table 1)

Group A: Direct Bonding vs AI

The Kruskal-Wallis comparison test showed a statistically significant difference between all the values; RMS (root mean square), minimum and maximum values with a p-value of <0.05 (Table 2).

Descriptive statistics on table 4 show 4 values with clinically significant differences in this group (>0.50mm). Mandibular lateral incisors (0.60mm), maxillary lateral incisors (0.56mm), maxillary second premolars (0.54mm) and maxillary first premolars (0.53mm).

A post-hoc Tukey test for multiple comparisons revealed significant differences between maxillary lateral incisors & maxillary second premolar bracket positioning when compared to the rest of the teeth units ($p<0.05$) (Tables 7&10) Also, statistically significant differences were found between mandibular lateral incisors when compared to the rest of the teeth <0.05. (Table 12) The teeth with the least number of differences within the groups were the maxillary central incisors and the mandibular second premolars. (Tables 6&15)

Group B: DB vs. Clinician

The Kruskal-Wallis comparison test showed a statistically significant difference between all the values; RMS (root mean square), minimum and maximum values with a p-value of <0.05 (Table 3).

Descriptive statistics on table 5 show 3 values with clinically significant differences in this group (>0.50mm). Maxillary second premolars (0.54mm) and maxillary first premolars (0.52mm) and mandibular second premolars (0.51mm)

A post-hoc Tukey test for multiple comparisons revealed significant differences between maxillary second and first premolars when compared to the rest of the teeth units ($p<0.05$) (Tables 19&20) Also, statistically significant differences were found between mandibular second premolars when compared to the rest of the teeth <0.05. (Table 25) The teeth with the least number of differences within the groups was the mandibular lateral incisors. (Table 22)

There were more discrepancies in Group A (DB vs AI) with 4 values over 0.50mm when compared to Group B (DB vs Clin) that only had 3 values over that threshold. On Group A the teeth with the highest discrepancy were the mandibular & maxillary lateral incisor; while in

Group B the teeth with the most discrepancy were the maxillary second and first premolar.

Discussion

For our study, it is important to make the distinction between statistically significant differences ($p<0.05$) and clinically significant differences. Assessment of clinical acceptability was based on the American Board of Orthodontics (ABO) objective grading system for dental casts. The ABO established that deviations from proper alignment of ≤0.50 mm are clinically acceptable.

We found more discrepancies in Group A (Direct bonding vs AI) than in Group B (Direct Bonding vs Virtual Clinician). We demonstrated that virtual indirect bonding whether is planned by AI or a clinician will differ from the direct bonding technique. Some factors that could had introduce some of those differences with direct bonding (in-vivo) are isolation issues, patient head position, source of light, stress, eye fatigue, among others.

In the literature, studies have been made comparing direct vs indirect bonding techniques but mostly in-vitro since in vivo conditions are more complex and unpredictable than in vitro experiments. Advances in technology and 3D superimposition software features have improve measuring the accuracy of indirect bonding.[45] Most of the related studies using 3D superimposition software to analyze bracket positioning discrepancies also have a linear and or angular measurements assessments.[11]

In our study we didn't use a coordinate measuring system since our goal was to discover if there were in fact bracket positioning differences regardless of the spatial direction of the differences. Previous studies reported in the literature that digital superimpositions provide more reliable and accurate data when compared with linear measurements. [37,45]

We decided to use the root mean square value as our measuring parameter because it allowed us to see the absolute numerical difference in the bracket positioning.[44] It's been a popular measurement in the literature since is less influenced by offset errors of positive or negative values that are usually related to linear measurements. [45]

Panayi et al. studied direct bonding, direct bonding assisted with loupes and indirect bonding. They had 18 patients and a sample of 298 permanent teeth. Their study found values higher than 0.45mm in the posterior teeth region. All measurements were found to be statistically significant different. They had linear and angular measurements instead of RMS values.[1]So we cannot do a direct comparison to our study, but they had a similar sample to our study and more discrepancies were found at the posterior area which is consistent with our findings (Group A U4&5's), Group B (U4,5&L5)

Conclusion

The aim of this study was to find if there were any significant or clinical differences between direct bonding (jn-vivo), virtual bonding aided by clinician and artificial intelligence bonding techniques. We rejected the null hypothesis and accepted the alternative hypothesis.

We found statistically and clinically significant differences between AI and Clinician when compared to direct bonding. With our data, we could infer that if we were to compare AI Vs Clinician, there might not be any clinically significant differences since the differences between this fall below 0.25mm. (Tables 4&5). To our best knowledge this

study is first of its kind, since in-vivo conditions are much more complex and unpredictable than in vitro experiments and will hopefully bring some more insight and knowledge to this emerging field of research.

Table 1: Test of Normality for Data

Shapiro-Wilk Normality Test			
	Statistic	**df**	**Significance**
RMS	0.80	26	<0.001
Min	0.98	26	<0.001
Max	0.98	26	<0.001

Table 2: Descriptive Statistics Kruskal-Wallis Group A (Direct bonding vs AI)

		Sum of Squares	df	Mean Square	F	Sig.
RMS	Between Groups	1.46	9	0.16	13.10	<.001
	Within Groups	3.35	270	0.01		
	Total	4.82	279			
Max.	Between Groups	0.73	9	0.08	11.11	<.001
	Within Groups	1.98	270	0.01		
	Total	2.72	279			
Min.	Between Groups	0.73	9	0.08	11.11	<.001
	Within Groups	1.98	270	0.01		
	Total	2.72	279			

Table 3: Descriptive Statistics Kruskal-Wallis Group B (Direct bonding vs Virtual Clinician

		Sum of Squares	df	Mean Square	F	Sig.
RMS	Between Groups	0.97	9	0.11	10.54	<.001
	Within Groups	2.75	270	0.01		
	Total	3.72	279			
Max.	Between Groups	0.56	9	0.06	5.91	<.001
	Within Groups	2.82	270	0.01		
	Total	3.37	279			
Min.	Between Groups	0.59	9	0.07	6.28	<.001
	Within Groups	2.83	270	0.01		
	Total	3.43	279			

Table 4: Descriptive Statistics Direct Bonding vs AI

TEETH	RMS	MAX	MIN (-)
U1	0.45 ± 0.11	0.82± 0.05	0.82 ± 0.05
U2	**0.56 ± 0.15**	0.82 ± 0.09	0.82 ± 0.09
U3	0.40 ± 0.06	0.73 ± 0.07	0.73 ± 0.07
U4	**0.53 ± 0.14**	0.83 ± 0.05	0.83 ± 0.05
U5	**0.54 ± 0.13**	0.84 ± 0.10	0.84 ± 0.10
L1	0.43 ± 0.10	0.78 ± 0.13	0.78 ± 0.13
L2	**0.60 ± 0.15**	0.91 ± 0.10	0.91 ± 0.11
L3	0.39 ± 0.06	0.74 ± 0.09	0.74 ± 0.09
L4	0.41 ± 0.08	0.76 ± 0.06	0.76 ± 0.06
L5	0.44 ± 0.08	0.78 ± 0.06	0.78 ± 0.06

Table 5: Descriptive Statistics Direct Bonding vs Virtual Clinician

TEETH	RMS	MAX	MIN (-)
U1	0.40 ± 0.03	0.72 ± 0.08	0.72 ± 0.09
U2	0.38 ± 0.06	0.74 ± 0.12	0.74 ± 0.12
U3	0.39 ± 0.05	0.73 ± 0.07	0.73 ± 0.07
U4	**0.52 ± 0.15**	0.83 ± 0.07	0.84 ± 0.07
U5	**0.54 ± 0.15**	0.84 ± 0.10	0.85 ± 0.10
L1	0.41 ± 0.07	0.79 ± 0.13	0.79 ± 0.13
L2	0.43 ± 0.09	0.81 ± 0.17	0.81 ± 0.17
L3	0.40 ± 0.06	0.74 ± 0.09	0.74 ± 0.09
L4	0.39 ± 0.04	0.75 ± 0.04	0.75 ± 0.04
L5	**0.51 ± 0.17**	0.82 ± 0.08	0.82 ± 0.08

Table 6: Post-hoc Direct Bonding vs AI maxillary central incisors

Teeth	Teeth	Mean Difference	Sig.
U1	U2	**-0.12**	**0.00**
	U3	0.05	0.84
	U4	-0.08	0.14
	U5	**-0.10**	**0.05**
	L1	0.02	1.00
	L2	**-0.16**	**<.001**
	L3	0.06	0.70
	L4	0.03	0.99
	L5	0.00	1.00

Table 7: Post-hoc Direct Bonding vs AI maxillary lateral incisors

Teeth	Teeth	Mean Difference	Sig.
U2	U1	**0.12**	**0.00**
	U3	**0.17**	**<.001**
	U4	0.03	0.98
	U5	0.02	1.00
	L1	**0.13**	**<.001**
	L2	-0.04	0.95
	L3	**0.17**	**<.001**
	L4	**0.15**	**<.001**
	L5	**0.12**	**0.00**

Table 8: Post-hoc Direct Bonding vs AI maxillary canines

Teeth	Teeth	Mean Difference	Sig.
U3	U1	-0.05	0.84
	U2	**-0.17**	**<.001**
	U4	**-0.13**	**<.001**
	U5	**-0.14**	**<.001**
	L1	-0.03	0.99
	L2	**-0.20**	**<.001**
	L3	0.01	1.00
	L4	-0.02	1.00
	L5	-0.04	0.89

Table 9: Post-hoc Direct Bonding vs AI maxillary first premolars

Teeth	Teeth	Mean Difference	Sig.
U4	U1	0.08	0.14
	U2	-0.03	0.98
	U3	**0.13**	**<.001**
	U5	-0.01	1.00
	L1	**0.10**	**0.03**
	L2	-0.07	0.30
	L3	**0.14**	**<.001**
	L4	**0.12**	**0.01**
	L5	0.09	0.11

Table 10: Post-hoc Direct Bonding vs AI maxillary second premolars

Teeth	Teeth	Mean Difference	Sig.
U5	U1	**0.10**	**0.05**
	U2	-0.02	1.00
	U3	**0.14**	**<.001**
	U4	0.01	1.00
	L1	**0.11**	**0.01**
	L2	-0.06	0.56
	L3	**0.15**	**<.001**
	L4	**0.13**	**0.00**
	L5	**0.10**	**0.04**

Table 11: Post-hoc Direct Bonding vs AI mandibular central incisors

Teeth	Teeth	Mean Difference	Sig.
L1	U1	-0.02	1.00
	U2	**-0.13**	**<.001**
	U3	0.03	0.99
	U4	**-0.10**	**0.03**
	U5	**-0.11**	**0.01**
	L2	**-0.17**	**<.001**
	L3	0.04	0.96
	L4	0.01	1.00
	L5	-0.01	1.00

Table 12: Post-hoc Direct Bonding vs AI mandibular lateral incisors

Teeth	Teeth	Mean Difference	Sig.
L2	U1	**0.16**	**<.001**
	U2	0.04	0.95
	U3	**0.20**	**<.001**
	U4	0.07	0.30
	U5	0.06	0.56
	L1	**0.17**	**<.001**
	L3	**0.21**	**<.001**
	L4	**0.19**	**<.001**
	L5	**0.16**	**<.001**

Table 13: Post-hoc Direct Bonding vs AI mandibular canines

Teeth	Teeth	Mean Difference	Sig.
L3	U1	-0.06	0.70
	U2	**-0.17**	**<.001**
	U3	-0.01	1.00
	U4	**-0.14**	**<.001**
	U5	**-0.15**	**<.001**
	L1	-0.04	0.96
	L2	**-0.21**	**<.001**
	L4	-0.02	1.00
	L5	-0.05	0.77

Table 14: Post-hoc Direct Bonding vs AI mandibular first premolars

Teeth	Teeth	Mean Difference	Sig.
L4	U1	-0.03	0.99
	U2	**-0.15**	**<.001**
	U3	0.02	1.00
	U4	**-0.12**	**0.01**
	U5	**-0.13**	**0.00**
	L1	-0.01	1.00
	L2	**-0.19**	**<.001**
	L3	0.02	1.00
	L5	-0.03	0.99

Table 15: Post-hoc Direct Bonding vs AI mandibular second premolars

Teeth	Teeth	Mean Difference	Sig.
L5	U1	0.00	1.00
	U2	**-0.12**	**0.00**
	U3	0.04	0.89
	U4	-0.09	0.11
	U5	**-0.10**	**0.04**
	L1	0.01	1.00
	L2	**-0.16**	**<.001**
	L3	0.05	0.77
	L4	0.03	0.99

Table 16: Post-hoc Direct Bonding vs Virtual Clinician maxillary central incisors

Teeth	Teeth	Mean Difference	Sig.
U1	U2	0.02	1.00
	U3	0.01	1.00
	U4	**-0.12**	**<.001**
	U5	**-0.14**	**<.001**
	L1	-0.01	1.00
	L2	-0.03	0.98
	L3	0.01	1.00
	L4	0.02	1.00
	L5	**-0.11**	**0.00**

Table 17 : Post-hoc Direct Bonding vs Virtual Clinician maxillary lateral incisors

Teeth	Teeth	Mean Difference	Sig.
U2	U1	-0.02	1.00
	U3	-0.01	1.00
	U4	**-0.14**	**<.001**
	U5	**-0.16**	**<.001**
	L1	-0.03	0.97
	L2	-0.05	0.63
	L3	-0.02	1.00
	L4	0.00	1.00
	L5	**-0.13**	**<.001**

Table 18: Post-hoc Direct Bonding vs Virtual Clinician maxillary canines

Teeth	Teeth	Mean Difference	Sig.
U3	U1	-0.01	1.00
	U2	0.01	1.00
	U4	**-0.13**	**<.001**
	U5	**-0.15**	**<.001**
	L1	-0.02	1.00
	L2	-0.04	0.88
	L3	-0.01	1.00
	L4	0.01	1.00
	L5	**-0.12**	**<.001**

Table 19: Post-hoc Direct Bonding vs Virtual Clinician maxillary first premolars

Teeth	Teeth	Mean Difference	Sig.
U4	U1	**0.12**	**<.001**
	U2	**0.14**	**<.001**
	U3	**0.13**	**<.001**
	U5	-0.02	1.00
	L1	**0.11**	**0.00**
	L2	**0.09**	**0.04**
	L3	**0.12**	**<.001**
	L4	**0.14**	**<.001**
	L5	0.01	1.00

Table 20: Post-hoc Direct Bonding vs Virtual Clinician maxillary second premolars

Teeth	Teeth	Mean Difference	Sig.
U5	U1	**0.14**	**<.001**
	U2	**0.16**	**<.001**
	U3	**0.15**	**<.001**
	U4	0.02	1.00
	L1	**0.13**	**<.001**
	L2	**0.11**	**0.00**
	L3	**0.14**	**<.001**
	L4	**0.15**	**<.001**
	L5	0.03	1.00

Table 21: Post-hoc Direct Bonding vs Virtual Clinician mandibular central incisors

Teeth	Teeth	Mean Difference	Sig.
L1	U1	0.01	1.00
	U2	0.03	0.97
	U3	0.02	1.00
	U4	**-0.11**	**0.00**
	U5	**-0.13**	**<.001**
	L2	-0.02	1.00
	L3	0.02	1.00
	L4	0.03	0.99
	L5	**-0.10**	**0.01**

Table 22: Post-hoc Direct Bonding vs Virtual Clinician mandibular lateral incisors

Teeth	Teeth	Mean Difference	Sig.
L2	U1	0.03	0.98
	U2	0.05	0.63
	U3	0.04	0.88
	U4	**-0.09**	**0.04**
	U5	**-0.11**	**0.00**
	L1	0.02	1.00
	L3	0.04	0.95
	L4	0.05	0.74
	L5	-0.08	0.09

Table 23: Post-hoc Direct Bonding vs Virtual Clinician mandibular canines

Teeth	Teeth	Mean Difference	Sig.
L3	U1	-0.01	1.00
	U2	0.02	1.00
	U3	0.01	1.00
	U4	**-0.12**	**<.001**
	U5	**-0.14**	**<.001**
	L1	-0.02	1.00
	L2	-0.04	0.95
	L4	0.01	1.00
	L5	**-0.12**	**<.001**

Table 24: Post-hoc Direct Bonding vs Virtual Clinician mandibular first premolars

Teeth	Teeth	Mean Difference	Sig.
L4	U1	-0.02	1.00
	U2	0.00	1.00
	U3	-0.01	1.00
	U4	**-0.14**	**<.001**
	U5	**-0.15**	**<.001**
	L1	-0.03	0.99
	L2	-0.05	0.74
	L3	-0.01	1.00
	L5	**-0.13**	**<.001**

Table 25: Post-hoc Direct Bonding vs Virtual Clinician mandibular second premolars

Teeth	Teeth	Mean Difference	Sig.
L5	U1	**0.11**	**0.00**
	U2	**0.13**	**<.001**
	U3	**0.12**	**<.001**
	U4	-0.01	1.00
	U5	-0.03	1.00
	L1	**0.10**	**0.01**
	L2	0.08	0.09
	L3	**0.12**	**<.001**
	L4	**0.13**	**<.001**

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APPENDICES

Appendix A: IRB Approval

IRB Administration Offices
UH IRB Phone: 216.844.1529
CWRU IRB Phone: 216.368.6925

INITIAL APPROVAL

Principal Investigator:	Tarek ElShebiny
Title:	Comparison between direct, virtual and artificial intelligence bonding techniques in Orthodontics
Submission Number:	STUDY20221525
IRB Office:	CWRU IRB
Approval Date:	7/21/2023
Effective Date:	7/21/2023
Approval End Date	N/A
Type of Submission:	Initial Study
Type of Review:	Expedited
Documents Reviewed:	• Recruitment form JCM, Category: Recruitment Materials; • HIPAA partial waiver, Category: Other; • Assent IRB, Category: Consent Form; • Consent IRB Final Edit.pdf, Category: Consent Form; • Protocol Johana Cortes-Mercado V4.2, Category: IRB Protocol;

The IRB has reviewed this submission.

- Per Federal regulation, changes MAY NOT be made to any element of the current research without prior IRB approval, except to eliminate an immediate and apparent hazard to subjects enrolled in the study.
- Per Federal regulation, the research may not continue beyond the Approval End date. You must submit a continuing review form 6-8 weeks before this Approval End date in order to maintain IRB approval. Failure to maintain IRB approval is human subjects non-compliance. Please note that even if your study falls into a category that does not require an Approval End date, the institution may require a yearly "check-in" to confirm the status of the study.

***Approval by the IRB does NOT mean that you have permission to start your study. Prior to starting your study, you may be required to obtain (1) a coverage analysis for studies that involve patient care, regardless of source of funding, and/or (2) a contract with the Sponsor of your study or an agreement with any third-party collaborator that

The UH IRB operates under HHS Federalwide Assurance (FWA) number 00003937 and IRB registration numbers 00000684, 00001691 and 00008600. The CWRU IRB operates under DHHS FWA00004428 and IRB registration number 00000683.

Appendix B: Abbreviation Key

3D: Three-dimension

DB: Direct Bonding

AI: Artificial Intelligence

CLIN: Clinician

CAD: Computer-Aided Design

CAD/CAM: Computer-Aided Design/Computer-Aided Manufacturing

CEREC: Chairside Economical Restoration of Esthetic Ceramics

CWRU: Case Western Reserve University

STL: Stereolithography

DIBS: digital indirect bonding system

IDBS: indirect bonding bracket system

PVS: polyvinyl siloxane

IO: IntraOral

RMS: Root Mean Square