ASSESSMENT OF VIRTUAL BRACKET REMOVAL BY ARTIFICIAL INTELLIGENCE AND THERMOPLASTIC RETAINER FIT

by

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Abstract

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Introduction:

Digital orthodontics is here to make our profession more accurate and efficient and the integration of artificial intelligence is no exception. The purpose of this study is to compare the accuracy of virtual bracket removal by artificial intelligence, to traditional bracket removal. A secondary objective is to compare the clinical fit of thermoplastic orthodontic retainers fabricated from 3D printed models created by each method.

Methods:

Thirty dental arches were scanned intraorally with the fixed labial orthodontic brackets in place, creating 30 STL files which were labeled pre-debond. For each patient, all brackets and residual adhesive were then clinically removed and an additional intraoral scan was taken and labeled post-debond. Each pre-debond scan was uploaded to the uDesign by uLab software, which uses artificial intelligence to virtually remove orthodontic brackets using 1-touch bracket identification. New STL files were created for each of the 30 arches and labeled virtual bracket removal (VBR). Best fit superimpositions were performed using Geomagic® Control X, data was collected as both numerical values and color-coded deviation maps. Superimposition data was segmented for each arch (anterior, posterior right, posterior left) to determine if arch location was a relevant factor. All post-debond and VBR STL files were 3D printed.

Thermoplastic retainers were fabricated on each 3D printed model. Retainers were delivered to patients and clinically graded by two practitioners.

Results:

There was a statistically significant difference of standard deviation and out of tolerance percentage values when comparing arch segments (anterior, posterior right, posterior left). There was no correlation between out of tolerance values and retainer fit evaluation among any of the graded variables. Grading scores for both evaluators show a statistically significant difference for evaluation of facial surface adaptation and snap fit acceptability between retainer fabrication methods.

Conclusion:

VBR by artificial intelligence is considered accurate enough to be used for fabrication of clinically acceptable thermoplastic orthodontic retainers.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS....3

ABSTRACT....4

LISTS OF TABLES....7

REVIEW OF LITERATURE....8

LITERATURE REVIEW REFERENCES....22

STATEMENT OF THESIS....29

MANUSCRIPT FOR PUBLICATION....30

MANUSCRIPT REFERENCES....48

APPENDICIES....50

A. IRB APPROVAL....50

B. ABBREVIATION KEY....51

C. RAW DATA....52

LISTS OF TABLES

Table 1: Descriptive Statistics of Full Arch Superimposition Data

Table 2:Descriptive Statistics of Arch Sextant Superimposition Data

Table 3: 1-Way ANOVA Out of Tolerance Percentage with Location as a Factor

Table 4: Faculty Evaluator Grading Results and Statistics

Table 5: Resident Evaluator Grading Results and Statistics

Table 6: Correlation of Out of Tolerance Percentage and Full Maxillary Arch Retainer Fit Scores

Table 7: Correlation of Out of Tolerance Percentage and Full Mandibular Arch Retainer Fit Scores

REVIEW OF LITERATURE

Conventional debond/retainer flow

In the late 1970s, the successful formulation of UV light curable bracket adhesives, allowed orthodontists to start bonding labial metal brackets, instead of the traditional banding.[1] Since this time, the process of braces removal has been standard among orthodontists. When patients were considered 'ready for debond' and not further tooth movement was required, each bracket was individually detached and residual adhesive mechanically removed. After appliance removal, dental impressions were taken and patients were reappointed for retainer delivery, ideally within the shortest amount of time as possible to prevent unwanted tooth movement.

Until the conception of virtual bracket removal, the only alternative to this traditional, debond, impress & reappoint process, was to impress with brackets in place, pour the impression in stone and manually scrape each bracket off stone casts. Utilizing this method, retainers could be pre-fabricated and delivered during the same appointment as appliance removal. After an exhaustive literature search, it was determined that this method has not been researched or assessed for accuracy.

Retention

As orthodontists know, our work does not cease when active appliances are removed. Maintaining a stable result and holding teeth in an ideal aesthetic and functional relationship is just as important as achieving that result in the first

place. How do we accomplish this? Orthodontic retention. The requirement for orthodontic retention was first explained by Dr. Emerson C. Angell in an 1860 article in Dental Cosmos (now Journal of the American Dental Association). Angell suggested 'orthodontic retention is needed to stabilize the result of an orthodontic treatment'.[2, 3] Even 160+ years later, this point is as relevant as ever. The need for orthodontic retention was reiterated very eloquently by Calvin Case in 1920:

> "If there is one part of orthodontia more than another that is absolutely indispensable to the success of this specialty and its establishment upon a firm foundation as one of the arts and sciences, it is the permanent retention of regulated teeth… what does this temporary pleasure and satisfaction to ourselves and our patients amount to, if we find in a few years that the very cases which create in us the greatest pride , are going back to their former malpositions and disharmonies, in spite of everything we have been able to do with retaining appliances." [4]

So, we know that retention of orthodontic tooth movement is crucial. But how long should the retention phase of treatment last? The length of time needed to stabilize orthodontic results is a highly debated subject. There are many destabilizing forces that can/will negatively affect post-treatment results such as: periodontal/gingival tissue forces, soft tissue balance, arch form, overjet, overbite, occlusal forces, facial growth and dentofacial aging. With all these factors in play, it's no surprise that post-treatment alteration in tooth position is unpredictable and variable. More importantly, we cannot pre-identify dentitions that will and will not relapse, or to what degree, thus long-term retention is commonly prescribed. [5]

Orthodontic Retainer Types

Orthodontic retainer designs have transitioned from fixed metals, to removable appliances and in modern orthodontics, sometimes a combination of both. For decades, labial steel wired removable retainers with acrylic baseplates have been the most popular long-standing option. This contemporary version of Dr. Charles Hawley's original 1919 design still plays a significant role in orthodontic retention.[6]

Originally introduced in the late 1950's, the concept of vacuum-formed (thermoplastic) retainers provided a sleeker alternative to previous removable retention options.[3] Since their introduction, thermoplastic retainers have been gaining popularity. The escalation of use came after the invention of a durable, thin, clear polymer that was more resistant to cracking and distortion than previous materials, created by DENTSPLY Raintree Essix.[7] The product was introduced 'as an esthetic, comfortable, and inexpensive modern alternative to traditional retainers.' A 2012 study from the Korean Journal of Orthodontics reported that patients were more cooperative with prescribed retainer wear when Essix retainers we given, in comparison to Hawley retainers. Additionally, this study found that retention characteristics of both Essix & Hawley retainers were similar. However, their investigation showed Essix retainers to be more effective at maintaining incisor positions during retention. That, along with the fact that Essix retainers have nothing to adjust,[8] takes some of the burden of retainer maintenance off the practitioner. Research has also shown that thermoplastic retainers are better accepted by adolescent patients,[9] versus Hawley retainers.

Thermoplastic retainer materials are now available for purchase from most dental supply companies, each with claims of better clarity, durability and

longevity. A 2016 study by Zhu and Lin investigated the survival time and patient reported comfort between thermoplastic retainers with 0.75 and 1.00mm thicknesses. The randomized control trial concluded that there was a significantly higher fracture rate with the 0.75mm retainer group than the 1.0mm group, with follow-up evaluations up to 12 months. However, this study reported no difference in patient reported comfort.[10] Could we take this information and deduce that thermoplastic retainers made with 1.0mm thick material is a better option, that's for each individual practitioner to decide for their practice.

There is a significant amount of geographic relation to prescribed fixed and removable retention protocols. The article reported that in the United States, the most commonly prescribed retainer combination is a maxillary arch thermoplastic removable retainer and a mandibular fixed retainer, with 80% of US orthodontists advising indefinite retention.[11] However, poor patient abidance is common, with 67% of patients fully discontinuing retainer wear after the second year of retention.[12]

Intraoral scanning

For the early adopters & innovators, the days of alginate dental impressions for retainer fabrication are fully a thing of the past. For the rest of us, we're navigating a world that floats somewhere between wanting to go fully digital and the unknown that comes with committing at 100%.

Faster, cleaner, easily transferable, more accurate and better tolerated by patients. These are all proven claims that have made the transition from analog (alginate and polyvinyl siloxane) dental impressions and plaster models to 'digital

impressions' with intraoral scanning technologies an obvious choice for dental professionals. Intraoral scanners capture surface data points of both hard and soft dental tissues for study, diagnosis, measurement, manipulation, treatment prediction & electronic storage of pre-, intra- and/or post-treatment information. 3D scanning in dentistry was pioneered by Dentsply Sirona in 1985 with the release of the chairside economical restoration of esthetic ceramics (CEREC) intraoral scanner. The purpose of the CEREC was to take digital 'impressions' to design fixed prosthetic restorations, within the realm of general dentistry and prosthodontics.[13] It wasn't until 1999 that 3D technology was introduced to the orthodontic community by Orthocad, who scanned orthodontic casts at their company headquarters in Poland for digital study/analysis.[14]

The integration of chairside intraoral scanning in university and private practice orthodontic settings occurred in 2006 when the iTero® (Align Technologies, San Jose, California) digital impression scanner was introduced. With a large introductory price tag, the integration of this technology was not initially feasible for common use. The list of companies now offering intraoral scanners has since grown, with each offering slightly different features to hold stake in the marketplace. Features such as size, weight, portability, cleanability, initial cost, monthly service fee, screen size/functionality, powder coating, user experience, scan speed, sensor sensitivity, data storage, auxiliary features (outcome simulator, caries detection) and more, factor into the decision on which intraoral scanner an orthodontist may choose. No matter the brand, every 3D intraoral

scanner has three major components: a mobile workstation to support data entry, a handheld camera wand to collect data and a monitor.[15]

The means of data collection, via white light or laser, varies by scanner to collect hundreds of thousands of measurements per inch and creating 3D representations of the original objects. The types of camera wand technology used with intraoral scanners are: triangulation, parallel confocal, accordion fringe interferometry (AFI), three-dimensional in-motion video and near infrared imaging (NIRI). The iTero element 2 uses parallel confocal imaging, which utilizes focused red and white laser light to tomographically slice object data and stitch is back together to create a final picture. Often this technology is referred to as 'point-and-stitch reconstruction'.[16]

The accuracy and reliability of intraoral scanning as an acceptable alternative to analog impression taking, has been exhaustively studied since the technology's introduction.[17, 18, 19] Scans taken with orthodontic brackets in place, have shown slight discrepancies, however all results were considered clinically acceptable, with 3D superimposition comparison.[20] We should, however, take into consideration that operator experience and skill level plays a crucial role in accurately capturing data with intraoral scanners, whether patients have orthodontic appliances in place or not.

A significant driving force towards the full transition to digital impressions is patient satisfaction. A 2015 study that investigated patient perceived burdens of dental treatments highlighted that patients reported traditional impressions 'unpleasant and burdensome'.[21] The study found that there was a statistically significant result of dissatisfaction with analog impressions for the following

parameters: pressure, impression consistency, taste, urge to gag, opening of the mouth for impression and impression removal. Moreover, when surveyed, patients reported they would rather seek treatment from practitioners who use digital impressions over those who take alginate impressions. When comparing types of intraoral scanners, a satisfaction questionnaire taken by orthodontic patients reported that intraoral scans taken with an iTero® scanner was significantly more comfortable, patient's experienced less pain and dry mouth, than with TRIOS (3Shape, Copenhagen, Denmark) scanner or alginate impressions.[22]

3D printing

Originally known as 'rapid prototyping' and invented in 1981 by Hideo Kodama of Japan,[23] 3D printing is an additive manufacturing process utilized by the automotive, aerospace, defense, healthcare industries and more. This technology utilizes engineering and computer-aided design (CAD) to create digital files that are then constructed, layer by layer, into solid objects. There are three commonly used 3D printing technologies utilized in modern dentistry, each be explained below.[24]

1. Fused Deposition Modeling (FDM)/ Fused Filament Fabrication (FFF)

   This technology falls under material extrusion processing, where a thermoplastic material is fed into a heated nozzle, melted and extruded onto a flat build platform. Thermoplastic material used for this method is often sold in spools of various colors and types of plastic. Objects

produced with this technique often have visible layer lines that may require additional processing/finishing, depending on their intended use. Additionally, print accuracy may be limited by nozzle diameter, making this a mediocre choice for dental applications.

2. Stereolithography (SLA)

   This technology utilizes high powered lasers to harden liquid resin and create a desired 3D shape, converting a photosensitive liquid into a solid. As with many 3D printing technologies, 3D items fabricated with these printers are built in a line-by-line and layer-by-layer fashion. Post-print processing of objects includes removal of excess/uncured resin and final cure.

3. Digital Light Processing (DLP)

   DLP technology uses a stationary source of projected ultraviolet light to partially cure complete layers of resin. The light sources of DLP printers are constructed from a large number of individual mirrors that can be directed towards or away from the resin, generating patterns of light and dark areas to construct each individual print layer. This light technology was invented by Larry Hornbeck in 1987 and soon after, utilized by Texas Instruments to create DLP projection.[25] As with SLA printed objects, the models fabricated from DLP printers also require post-print processing to remove excess/uncured resin before final cure.

With each of the above-described 3D printing modalities, there are customizable print settings to alter the print orientation, layer height, and exposure time. In addition, varying printer costs, required maintenance, printer

size, print time and ease of use, may lure a practitioner to one printer technology or brand.

A 2018 study by Kim, investigated the precision and trueness of 3D printed dental models.[26] The research compared scans of models printed with SLA, DLP, FFF and PolyJet printers against a reference models. The results showed that DLP models were more precise than SLA and FFF models, and highlighted that print times and print layer heights varied among the four printers. In another 2018 study, authors concluded that models produced with DLP printing technology produced a clinically acceptable results with high accuracy, and may serve as a replacement for stone models.[27]

Digital Orthodontics

While many university orthodontic departments and orthodontic practices have been using digital technologies for decades,[28] committing to a fully digital practice brings many new challenges. Digital technologies in orthodontics are utilized in many capacities including intraoral scanning, 3D printing, orthognathic surgical planning, bracket design and virtual bracket removal, just to name a few. An orthodontic 'digital workflow' would include digital file acquisition followed by viewing, editing and printing of digital files. This shift to a fully digital orthodontic practice requires a serious financial investment and proper professional training.[29]

The use of digital technology to remove orthodontic brackets was first investigated for accuracy by Dr. Chamberlain-Umanoff in 2019. Her thesis research project, Assessment of 3D surface changes following virtual bracket

removal, used Ortho Analyzer and Meshmixer software to digitally remove brackets from orthodontic models. The results of this research showed that VBR of posterior tooth segments showed least accuracy.[30] Another investigation of VBR was completed by Marsh et al in 2020.[31] The study compared virtual bracket removal (VBR) by three different methods (in-office Meshmixer software, Orthodent Laboratory, New England Orthodontic Laboratory). The authors concluded that the least accurate areas for VBR were second premolars and first molars, with first molars showing the greatest surface change after VBR and greatest amount of insufficient bracket removal. Additionally, there was a significant difference in the results produced by three different virtual bracket removal methods, but the difference was not considered clinically relevant. Other important findings from this study included: decreased practice cost and decreased turnaround time with in-office virtual bracket removal. An important point to highlight, studies have shown that orthodontic relapse can begin as soon as two hours after appliance removal.[32] If proper fitting retainers can be pre-fabricated and placed at the time of debond, the stabilization phase can begin even sooner.

Artificial intelligence

The term 'artificial intelligence' was coined by Dr. Johnathan McCarthy on August 31st 1955, in a proposal for a summer research project at Dartmouth College in Hanover, New Hampshire. In the proposal, the authors explained how the project's intention was 'an attempt to find out how to make machines use language, form abstractions and concepts, solve kinds of problems now reserved

for humans and improve themselves'.[33] The Oxford English Dictionary defines artificial intelligence as: 'the theory and development of computer systems able to perform tasks that normally require human intelligence'.[34] The key aspects of artificial intelligence are: artificial intelligence, machine learning, neural networks, and deep learning.

The backbone of artificial intelligence (AI) is machine learning. Machine learning uses algorithms to make predictions based on data sets gathered from a myriad of research disciplines. Machine learning then analyzes data and builds a neural network that functions like the human brain. An established neural network can then be used for deep learning, which is used to automatically recognize patterns and improve future detection.[35, 36]

As discussed previously, digital orthodontics is here to make our profession more accurate and efficient and the integration of AI is no exception. Within orthodontics, AI has been used for things such as automatic anatomy detection, cephalometric analysis, orthodontic treatment predictions, automatic tooth segmentation and more. A 2010 study by Xie investigated the accuracy of AI in deciding whether an extraction or non-extraction treatment plan would be most beneficial to reduce dental malocclusions, by using lateral cephalometric images (data points anterior teeth uncovered by incompetent lips and IMPA). The authors concluded that AI was able to correctly diagnose, with 80% accuracy, whether malocclusions in patients 11-15 years of age 'required' extraction.[37] Another study, published in 2016, also investigated the implementation of decision tree, for AI to diagnose the need for extractions using multiple extraction

patterns. The study concluded that there was a 93% success rate for AI diagnosis extraction vs non-extraction and 84% for specific extraction pattern.[38]

A 2021 systematic review by Monill-Gonzáles et al, explained that AI in orthodontics could be most valuable to decrease observer errors and may be most useful for time consuming or high precision procedures. The authors also underline that AI is just another tool and final health decisions will always be the clinicians' responsibility.[39]

uLab Systems

Founded in 2015, uLab Systems is a privately funded software technology company known for its digital orthodontic treatment planning platform. The platform utilizes AI-assisted treatment planning and has a self-proclaimed 'deep understanding of orthodontic biomechanics' to increase the efficiency of orthodontic treatment plans.[40]

Since its inception, uLab Systems has grown to not only offer orthodontic treatment planning, but also aligner manufacturing, custom aligner packaging and 1-touch digital debond of fixed orthodontic cases to fabricate retainers.

The 1-touch digital debond feature is completed by first uploading STL scan files, choosing the bracket removal feature and simply clicking on each bracket to 'mark' for removal. The artificial intelligence in the software will identify the entirety of each bracket and virtually remove it from the digital model. Additional smooth, scalpel, cut & fill and brush features are available to fine tune bracket removal and residual artifacts. The additional features were not

utilized for this project, as our aim was to evaluate the 1-touch digital bracket removal feature as a stand alone tool.

uLab System's corporate headquarters and manufacturing is in Memphis, Tennessee. In 2021, uLab Systems received grant funding by the state to enable expansion of its manufacturing facility, with a promise to create more than 230 additional jobs over the next five years. uLab prides itself on quick treatment plan turnaround time and quick aligner delivery to allow it's doctors to begin orthodontic treatments sooner.[41, 42]

Geomagic® Control X™

The professional engineering software, Geomagic , was created in 1997 by Ping Fu and Herbert Edelsbrunner. The original aim for the software was to enable customized manufacturing with 3D printers and was used for fabricating personalized shoes, prosthetic limbs, NASA spaceship repair parts and more.[43] In its early days, Geomagic experienced financial woes which almost took the company to bankruptcy. However, in 2001, a $1.8 million business contract with Align Technologies changed the companies trajectory. Proceeds from the deal allowed the company to switch from direct sales to resellers, which significantly reduced costs and allowing for long-term exponential growth.[44] Geomagic was acquired by 3D systems in 2013 and is now considered the Gold-Standard in comparison engineering software.

This sophisticated 3D CAD/CAM software can be used to inspect and interpret digital scan data.[45] With Geomagic software, input data can be compared using best-fit surface alignment via thousands of data points, to

provide information such as maximum and mean distances (positive and negative differences) and standard deviation between digital models. Deviation color maps can be easily created with adjustable distance limitations, for visualization of discrepancy locations and amounts.[46] In the literature, Geomagic has been used to evaluate the accuracy of other software products, aiming to replicate its success.[47]

Dental research has utilized Geomagic Control software to make evaluations in the realms of orthodontics, prosthodontics, restorative dentistry, surgery, implantology and more. As an example, a 2013 study by Nichols et al, used Geomagic Control X to assess the reproducibility of indirectly bonded orthodontic brackets by an orthodontist at different timepoints.[48] Another research article, by Edelmann et al, used Geomagic Control X to investigate the effect of digitally designed aligner thickness on the thickness of the corresponding 3-dimentional (3D)-printed aligner.[49]

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STATEMENT OF THESIS

Objective: The purpose of this study is to determine the accuracy of virtual bracket removal by artificial intelligence, with uDesign by uLab Systems software, when compared to traditional bracket removal. Additionally, thermoplastic orthodontic retainers were fabricated from 3D printed models created by each method, to evaluate any clinically observable difference in retainer fit.

Null Hypothesis: There is no difference in the accuracy of virtual versus traditional orthodontic bracket removal.
There is no difference in the fit acceptability of thermoplastic retainers fabricated from virtually debonded models and traditionally debonded models.

Alternative Hypothesis: Virtually bracket removal produces a significantly different result from traditional bracket removal methods. This translates to a lower clinical acceptability of thermoplastic retainers fabricated from VBR models.

MANUSCRIPT FOR PUBLICATION

ASSESSMENT OF VIRTUAL BRACKET REMOVAL BY ARTIFICIAL INTELLIGENCE AND THERMOPLASTIC RETAINER FIT

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ASSESSMENT OF VIRTUAL BRACKET REMOVAL BY ARTIFICIAL INTELLIGENCE AND THERMOPLASTIC RETAINER FIT

Abstract

By

AMANDA EDEN PARADIS

Introduction:

Digital orthodontics is here to make our profession more accurate and efficient and the integration of artificial intelligence is no exception. The purpose of this study is to compare the accuracy of virtual bracket removal by artificial intelligence, to traditional bracket removal. A secondary objective is to compare the clinical fit of thermoplastic orthodontic retainers fabricated from 3D printed models created by each method.

Methods:

Thirty dental arches were scanned intraorally with the fixed labial orthodontic brackets in place, creating 30 STL files which were labeled pre-debond. For each patient, all brackets and residual adhesive were then clinically removed and an additional intraoral scan was taken and labeled post-debond. Each pre-debond scan was uploaded to the uDesign by uLab software, which uses artificial intelligence to virtually remove orthodontic brackets using 1-touch bracket identification. New STL files were created for each of the 30 arches and labeled virtual bracket removal (VBR). Best fit superimpositions were performed using Geomagic® Control X, data was collected as both numerical values and color-coded deviation maps. Superimposition data was segmented for each arch (anterior, posterior right, posterior left) to determine if arch

location was a relevant factor. All post-debond and VBR STL files were 3D printed. Thermoplastic retainers were fabricated on each 3D printed model. Retainers were delivered to patients and clinically graded by two practitioners.

Results:

There was a statistically significant difference in standard deviation and out of tolerance percentage values when comparing traditional debonded arches and virtually debonded arches, when using sextant locations as a factor (anterior, posterior right, posterior left).

Grading scores for both evaluators show a statistically significant difference for evaluation of facial surface adaptation and snap fit acceptability between retainer fabrication methods. However, there was no correlation between out of tolerance values and clinical retainer fit evaluation among any of the graded variables in either the maxillary or mandibular arches.

Conclusion:

VBR by artificial intelligence is considered accurate enough to be used for fabrication of clinically acceptable thermoplastic orthodontic retainers.

Introduction:

In the late 1970s, the successful formulation of UV light curable bracket adhesives, allowed orthodontists to start bonding labial metal brackets, instead of the traditional banding.[1] Since this time, the process of braces removal has been standard among orthodontists. When patients were considered 'ready for debond' and not further tooth movement was required, each bracket was individually detached and residual adhesive mechanically removed. After appliance removal, dental impressions were taken and patients were reappointed for retainer delivery, ideally within the shortest amount of time as possible to prevent unwanted tooth movement.

Until the conception of virtual bracket removal (VBR), the only alternative to this traditional, debond, impress & reappoint process, was to impress with brackets in place, pour the impression in stone and manually scrape each bracket off stone casts. Utilizing this method, retainers could be pre-fabricated and delivered during the same appointment as appliance removal. After an exhaustive literature search, it was determined that this method has not been researched or assessed for accuracy.

Orthodontic retainer designs have transitioned from fixed metals, to removable appliances and in modern orthodontics, sometimes a combination of both. For decades, labial steel wired removable retainers with acrylic baseplates have been the most popular long-standing option. This contemporary version of Dr. Charles Hawley's original 1919 design still plays a significant role in orthodontic retention.[2]

Originally introduced in the late 1950's, the concept of vacuum-formed (thermoplastic) retainers provided a sleeker alternative to previous removable retention options.[3] Since their introduction, thermoplastic retainers have been gaining popularity. The escalation of use came after the invention of a durable, thin, clear polymer that was more resistant to cracking and distortion than previous materials, created by DENTSPLY Raintree Essix.[4] The product was introduced 'as an esthetic, comfortable, and inexpensive modern alternative to traditional retainers.' Research has shown that thermoplastic retainers are better accepted by adolescent patients,[5] versus Hawley retainers. Thermoplastic retainer materials are now available for purchase from most dental supply companies, each with claims of better clarity, durability and longevity.

Faster, cleaner, easily transferable, more accurate and better tolerated by patients. These are all proven claims that have made the transition from analog (alginate and polyvinyl siloxane) dental impressions and plaster models to 'digital impressions' with intraoral scanning technologies an obvious choice for dental professionals. Intraoral scanners capture surface data points of both hard and soft dental tissues for study, diagnosis, measurement, manipulation, treatment prediction & electronic storage of pre-, intra- and/or post-treatment information.

While many orthodontic departments and practices have been using various digital technologies for decades[6], committing to a fully digital practice brings many new challenges. Digital technologies in orthodontics are utilized in many capacities including intraoral scanning, 3D printing, surgical planning, bracket design, virtual bracket placement and virtual bracket removal, just to name a few.

The use of digital technology to remove orthodontic brackets was first investigated for accuracy in 2020 at the University of Southern California[7]. The study compared VBR by three different software/labs. The authors concluded that while there was a significant difference in the results produced by three different virtual bracket removal methods, this was not considered clinically relevant. Other important findings from this study included: decreased practice cost and decreased turnaround time with in-office virtual bracket removal. If we can utilize AI to accomplish a task that is just as accurate, but less expensive and takes less time, then this project could be a great contribution to orthodontics.

Methods:

The institutional review board at Case Western Reserve University (CWRU) approved this prospective clinical study. Informed consent and verbal assent were obtained from legal guardians and patients, respectively.

The inclusion criteria for this study were as follows: (1) subjects have full permanent dentition, (2) subjects being treated at CWRU graduate orthodontic clinic, (3) subjects finishing orthodontic treatment with full fixed labial brackets, (4) subjects deemed ready for orthodontic appliance removal and all treatment objectives met. The exclusion criteria for this study were as follows: (1) subjects have gross caries, (2) subjects not a candidate for thermoplastic retainers, (3) subjects with gingival overgrowth that may make virtual bracket removal difficult to accomplish, (4) subjects requiring maxillary fixed retainer in combination with maxillary removable retainer. One patient was excluded for poor scan quality.

The sample consisted of 30 dental arches (17 maxillary, 13 mandibular) of 17 patients in active treatment the CWRU graduate orthodontic clinic. The age range of patients included was 14 to 36, with 11 females and 6 males making up the research sample.

For each patient, arches were scanned intraorally with the fixed labial orthodontic brackets in place, with the iTero element 2 intraoral scanner, creating an STL files which were labeled pre-debond. During the same appointment, all brackets and residual adhesive were then clinically removed, and an additional intraoral scan was taken and labeled post-debond. Each scan file was automatically postprocessed and exported as a virtual model STL file.

Each pre-debond scan was then uploaded to the uDesign by uLab Systems software (version 7.0), which uses artificial intelligence to virtually remove orthodontic brackets using 1-touch bracket identification. uDesign's 1-touch virtual bracket removal protocol was used in this study without the use of any additional carving, smoothing, scalpel or filling tools. Each completed VBR arch was processed into a new STL file which was labeled VBR.

Two groups were compared (all arches were included). Group 1 was the control group that consisted of digital arch models from post-debond scans. Group 2 was the experimental group that consisted of VBR digital arch models.

For 3D evaluation of VBR accuracy, models of both groups were imported into Geomagic Control X software. Each VBR model was evaluated with Geomagic using the following arch segmentations: full maxillary arch, full mandibular arch, maxillary anterior, maxillary right posterior, maxillary left posterior, mandibular anterior, mandibular right posterior, mandibular left posterior. Best fit superimpositions were performed for each

segment. Superimposition data was collected as both numerical values and color-coded deviation maps. A 0.25mm threshold was set and any points that deviated more than 0.25mm in the positive or negative directions were considered to be beyond the upper and lower bounds, respectively. In regards to color mapping, green hues indicate no surface difference and red or blue indicates surface changes of ≥0.3mm in positive (red) or negative (blue) directions.

All post-debond and VBR STL files were 3D printed using the Sprintray 95 printer at 100-µm print layer height in horizontal orientation and the post processed using manufacturers guidelines.

Two thermoplastic retainers were fabricated for each arch with Zendura A material in 1.0mm thickness. One from the post-debond and one from the VBR generated models, using the Great Lakes dental Mini Biostar then trimmed and polished. Retainers were delivered to patients, and the fit of each independently graded by one board certified orthodontic faculty and one resident evaluator. Each retainer was graded in the following categories: self-retention, cervical margin fit, stability, snap fit, facial surface adaptation, anterior seat (incisors, canines), posterior seat (premolars, molars). A 0-2 grading scale was used, with 0=clinically unacceptable, 1= clinically acceptable, 2= clinically ideal.

Results:

Descriptive statistics of the Geomagic® Control X superimposition data, using traditionally debonded full arches and the virtually debonded full arches, can be seen in Table 1.

Arches were then segmented into sextants (anterior, posterior right, posterior left) to determine if location was a factor. Descriptive statistics for segmented arch data can be found in Table 2.

1-way analysis of variance (ANOVA) test showed a statistically significant difference of both standard deviation and out of tolerance percentage values when comparing arch segments (maxillary anterior, maxillary right posterior, maxillary left posterior, mandibular anterior, mandibular right posterior, mandibular left posterior) with a p-value of <0.01 (Table 3).

Clinical evaluation data for the faculty evaluator can be found in Table 4. 1-way ANOVA testing of the faculty evaluator's scores showed statistically significance in scoring of both snap fit and facial surface adaptation categories.

Clinical evaluation data for the resident evaluators can be found in Table 5. 1-way ANOVA testing of the resident evaluator's scores showed statistically significance in scoring of cervical margin fit, snap fit, facial surface adaptation and molar seat categories.

There was no correlation between out of tolerance percentage and retainer fit evaluation among any of the graded variables in the maxillary arch (Table 6). There was no correlation between out of tolerance percentage and retainer fit evaluation among any of the graded variables in the mandibular arch (Table 7).

Discussion:

In orthodontics, the word digital is often synonymous with greater efficiency and increased patient satisfaction.[8] Previous studies have investigated the accuracy of virtual bracket removal using both in-office and orthodontic

laboratory services, and have shown both to be accurate. [7, 9] Unfortunately, some bracket removal software options included intricate, time-consuming protocols or are only available for in-office use at a high cost. uDesign by uLab Systems was chosen for this project because it is an innovative, user-friendly and free-to-download software with many available features. The uDesign VBR tool works with one single click on each bracket by the operator to 'mark', then artificial intelligence (AI) identifies the entirety of each bracket to virtually remove, leaving a smooth tooth surface. Additional smooth, scalpel, cut & fill and brush features are available to fine tune bracket removal and residual artifacts. The additional features were not utilized for this project, as our aim was to evaluate the 1-touch VBR feature as a stand-alone tool. VBR by artificial intelligence with uDesign software can be performed on digital models obtained by any intraoral scanner. The iTero element 2 was used in this clinical study because it was readily available at the CWRU orthodontic clinic.

3D superimposition comparison results were obtained using Geomagic Control X software. This sophisticated 3D CAD/CAM software can be used to inspect and interpret digital scan data.[45] With Geomagic software, input data can be compared using best-fit surface alignment via thousands of data points, to provide information such as maximum and mean distances (positive and negative differences) and standard deviation between digital models. Deviation color maps can be easily created with adjustable tolerance and distance limitations, for visualization of discrepancy locations and amounts.[10] Superimposition accuracy was verified in this project by using color mapping to ensure that any reported deviation between models was true and not because of

superimposition errors. The selection tool was then used to create three sextants per arch (anterior, posterior right, posterior left).

The results of this study show that there was a statistically significant difference in the standard deviation values and out of tolerance values, when comparing all arch sextants to each other. Out of tolerance percentages represent the insufficient or excessive removal of orthodontic brackets, which was would have a negative effect on the fit of thermoplastic retainers made from VBR generated models. However, there was no correlation found between out of tolerance values and higher or lower clinical evaluation fit grading scores in any of the scoring parameters.

One limitation of this clinical study was the possibility of residual adhesive or unintentional removal of tooth structure after debond. However, the only way to assess the accuracy of VBR for retainer fabrication was removal of all appliances and use of the post-debond scan as reference to be able to clinically evaluate retainer fit.

Future studies could focus on VBR of other orthodontic appliances not evaluated in this study, such as clear aligner attachments or lingual brackets. Additionally, multiple in-office software types could be compared for VBR accuracy or VBR completed by clinicians at various stages of their career (dental assistants vs dental students vs orthodontists)

Conclusion:

In this prospective clinical study, the hypothesis that VBR produces a significantly different result from traditional bracket removal was confirmed (Table 3).

Retainers fabricated from traditionally debonded models were graded significantly higher than those fabricated from virtually debonded models in the categories of snap fit and facial surface adaptation by both clinical evaluators. However, there was no correlation between out of tolerance percentages and any retainer fit parameters.

Retainers fabricated from both post-debond models and VBR models were considered clinically acceptable for all arches. Thus, when using this study as a reference, its been confirmed that virtual bracket removal by artificial intelligence produces models that can be reliably used to fabricate thermoplastic retainers with acceptable fit.

Table 1: Descriptive Statistics of Full Arch Superimposition Data

Full Arch Superimposition Statistics				
		N	Mean	Standard Deviation
Deviation	Full Maxillary Arch	17	.1233	.03385
	Full Mandibular Arch	13	.1266	.03347
Out of Tolerance %	Full Maxillary Arch	17	7.1225	4.91362
	Full Mandibular Arch	13	8.1269	6.61359

Table 2: Descriptive Statistics of Arch Sextant Superimposition Data

Arch Sextant Superimposition Statistics				
		N	Mean	Standard Deviation
Deviation	Maxillary Anterior	17	.0879	.02368
	Maxillary Right Posterior	17	.1645	.07193
	Maxillary Left Posterior	17	.1595	.04860
	Mandibular Anterior	13	.1413	.03679
	Mandibular Right Posterior	13	.1338	.03853
	Mandibular Left Posterior	13	.1360	.04643
Out of Tolerance %	Maxillary Anterior	17	2.7712	3.18170
	Maxillary Right Posterior	17	13.7111	8.23516
	Maxillary Left Posterior	17	12.9489	7.88171
	Mandibular Anterior	13	9.2733	5.71317

	Mandibular Right Posterior	13	8.2790	5.70059
	Mandibular Left Posterior	13	8.6875	5.91969

Table 3: Out of Tolerance Percentage with Location as a Factor

1-way ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Deviation	.066	7	.009	4.805	<.001
Out of Tolerance %	1379.645	7	197.092	5.070	<.001

Table 4: Faculty Evaluator Grading Results and Statistics

	Retainer	Mean	Standard Deviation	Significance
Self-Retention	Post-Debond	1.9667	.18257	.561
	VBR	1.9333	.25371	
Cervical Margin Fit	Post-Debond	1.9667	.18257	.002
	VBR	1.6667	.47946	
Stability	Post-Debond	1.9667	.18257	.561
	VBR	1.9333	.25371	
Snapfit	Post-Debond	1.9333	.25371	<.001
	VBR	1.5333	.50742	
Facial Surface Adaption	Post-Debond	2.000	.00000	<.001
	VBR	1.5667	.50401	
Incisor Seat	Post-Debond	2.0000	.00000	.155
	VBR	1.9333	.25371	

Canine Seat	Post-Debond	2.0000	.00000	.155
	VBR	1.9333	.25371	
Premolars Seat	Post-Debond	1.9667	.18257	.088
	VBR	1.8333	.37905	
Molar Seat	Post-Debond	1.9667	.18257	.023
	VBR	1.7667	.43018	

Table 5: Resident Evaluator Grading Results and Statistics

	Retainer	Mean	Standard Deviation	Significance
Self-Retention	Post-Debond	2.0000	.00000	.039
	VBR	1.8667	.34575	
Cervical Margin Fit	Post-Debond	1.9000	.30513	<.001
	VBR	1.2667	.44978	
Stability	Post-Debond	1.9667	.18257	.088
	VBR	1.8333	.37905	
Snapfit	Post-Debond	1.9667	.18257	<.001
	VBR	1.6000	.49827	
Facial Surface Adaption	Post-Debond	2.0000	.00000	<.001
	VBR	1.5667	.50401	
Incisor Seat	Post-Debond	1.9667	.18257	.011
	VBR	1.7333	.44978	
Canine Seat	Post-Debond	1.9333	.25371	.133
	VBR	1.8000	.40684	
Premolars Seat	Post-Debond	2.0000	.00000	.002

	VBR	1.7333	.44978	
Molar Seat	Post-Debond	1.9667	.18257	<.001
	VBR	1.6000	.49827	

Table 6: Correlation of Out of Tolerance Percentage and Full Maxillary Arch Retainer Fit Scores

	Out of Tolerance Correlations- Full Maxillary Arch	
Self Retention	Pearson Correlation	-.205
	Sig. (2-tailed)	.429
Cervical Margin Fit	Pearson Correlation	-.046
	Sig. (2-tailed)	.861
Stability	Pearson Correlation	.[a]
	Sig. (2-tailed)	.
Snap Fit	Pearson Correlation	-.079
	Sig. (2-tailed)	.764
Facial Surface Adaptation	Pearson Correlation	-.024
	Sig. (2-tailed)	.929
Incisor Seat	Pearson Correlation	-.175
	Sig. (2-tailed)	.502
Canine Seat	Pearson Correlation	.100
	Sig. (2-tailed)	.703
Premolar Seat	Pearson Correlation	.092
	Sig. (2-tailed)	.725
Molar Seat	Pearson Correlation	-.108
	Sig. (2-tailed)	.681

a. Cannot be computed because at least one of the variables is constant.

Table 7: Correlation of Out of Tolerance % and Full Mandibular Arch Retainer Fit Scores

	Out of Tolerance Correlations- Full Mandibular Arch	
Self Retention	Pearson Correlation	-.394
	Sig. (2-tailed)	.183
Cervical Margin Fit	Pearson Correlation	-.336
	Sig. (2-tailed)	.262
Stability	Pearson Correlation	.[a]
	Sig. (2-tailed)	.
Snap Fit	Pearson Correlation	-.233
	Sig. (2-tailed)	.444
Facial Surface Adaptation	Pearson Correlation	.002
	Sig. (2-tailed)	.995
Incisor Seat	Pearson Correlation	-.414
	Sig. (2-tailed)	.159
Canine Seat	Pearson Correlation	-.359
	Sig. (2-tailed)	.229
Premolar Seat	Pearson Correlation	-.394
	Sig. (2-tailed)	.183
Molar Seat	Pearson Correlation	-.394
	Sig. (2-tailed)	.183

a. Cannot be computed because at least one of the variables is constant.

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Appendicies

Appendix A: IRB Approval

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

APPROVAL

Principal Investigator:	Tarek ElShebiny
Title:	ASSESSMENT OF VIRTUAL BRACKET REMOVAL BY ARTIFICIAL INTELLIGENCE AND THERMOPLASTIC RETAINER FIT
IRB Number:	STUDY20211497
Submission Number:	MOD00022571
IRB Office:	CWRU IRB
Approval Date:	6/17/2022
Effective Date:	6/17/2022
Approval End Date:	N/A
Type of Submission:	Modification
Type of Review:	Expedited
Documents Reviewed:	• IRB Protocol, Category: IRB Protocol; • Consent, Category: Consent Form;

The IRB 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 may receive UH or CWRU patient information in any format. Please ensure that all required approvals are obtained before initiation of research activity. ***

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

AI: Artificial Intelligence

CAD: Computer-Aided Design

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

CEREC: Chairside Economical Restoration of Esthetic Ceramics

CWRU: Case Western Reserve University

DLP: Digital Light Processing

FDM: Fused Deposition Modeling

FFF: Fused Filament Fabrication

IMPA: Incisor Mandibular Plane Angle

SLA: Stereolithography

STL: Stereolithography

UV: Ultraviolet

VBR: Virtual Bracket Removal

Appendix C: Superimposition Raw Data

Section	Min	Max	Avg	RMS	Std.Dev	Var	In Tol (%)	Out Tol %
Full Upper	-0.4862	0.5704	0.0294	0.1014	0.097	0.0094	96.3015	3.6985
U Anterior	-0.3153	0.392	0.0373	0.0935	0.0857	0.0074	97.7714	2.2286
UL Posterior	-0.1515	0.4067	0.0398	0.1016	0.0935	0.0087	95.7485	4.2515
UR Posterior	-0.4862	0.7705	0.0375	0.1541	0.1495	0.0223	90.9755	9.0245
L Anterior	-0.4316	0.7103	0.1137	0.186	0.1472	0.0217	81.5602	18.4398
Full Lower	-0.5634	0.5636	0.0307	0.1309	0.1272	0.0162	92.3389	7.6611
LL Posterior	-0.4173	0.5194	-0.0096	0.1184	0.118	0.0139	94.8007	5.1993
LR Posterior	-0.5087	0.5087	-0.0255	0.1093	0.1063	0.0113	95.5792	4.4208
Full Upper	-0.4447	0.4453	0.0004	0.0997	0.0997	0.0099	96.9189	3.0811
U Anterior	-0.2658	0.4025	0.0044	0.1003	0.1002	0.01	97.9379	2.0621
UL Posterior	-0.4839	0.4859	0.0139	0.1095	0.1086	0.0118	94.9121	5.0879
UR Posterior	-0.5151	0.4616	-0.016	0.1177	0.1166	0.0136	93.8381	6.1619
Full Lower	-0.4932	0.4928	-0.0195	0.1141	0.1125	0.0126	96.1676	3.8324
L Anterior	-0.4142	0.5626	0.0368	0.1314	0.1262	0.0159	93.1065	6.8935
LL Posterior	-0.4573	0.3085	-0.0466	0.1071	0.0965	0.0093	97.0681	2.9319
LR Posterior	-0.5039	0.2679	-0.0724	0.1033	0.0736	0.0054	98.8401	1.1599
Full Upper	-0.5361	0.5376	0.0132	0.1146	0.1138	0.013	94.4846	5.5154
U Anterior	-0.414	0.4146	0.0128	0.096	0.0952	0.0091	96.5685	3.4315
UL Posterior	-0.5619	0.8259	0.0433	0.1922	0.1873	0.0351	85.8639	14.1361
UR Posterior	-0.4414	0.5479	0.0193	0.1281	0.1266	0.016	92.6648	7.3352
Full Lower	-0.6444	0.8924	0.0191	0.1611	0.16	0.0256	88.8563	11.1437
L Anterior	-0.3671	0.5687	0.0262	0.1365	0.134	0.018	91.3555	8.6445
LL Posterior	-1.3128	1.3146	0.0246	0.1853	0.1837	0.0337	87.3803	12.6197
LR Posterior	-0.5767	0.7269	0.0114	0.1787	0.1783	0.0318	85.8552	14.1448
Full Upper	-0.3356	0.684	0.0435	0.1261	0.1183	0.014	94.1987	5.8013
U Anterior	-0.1637	0.3292	0.0193	0.0722	0.0696	0.0048	99.6477	0.3523
UL Posterior	-0.4245	0.7502	0.0659	0.181	0.1686	0.0284	85.944	14.056
UR Posterior	-0.2368	1.0016	0.0768	0.2197	0.2058	0.0424	83.675	16.325
Full Upper	-1.1802	1.1882	0.0981	0.2424	0.2216	0.0491	78.3879	21.6121
U Anterior	-0.4856	0.6681	0.0304	0.1626	0.1597	0.0255	87.8754	12.1246
UL Posterior	-1.7185	1.6323	0.1971	0.4208	0.3718	0.1382	68.4139	31.5861

UR Posterior	-1.0884	0.641	0.1453	0.2433	0.1951	0.0381	70.3024	29.6976
Full Lower	-0.4828	0.7418	0.044	0.1684	0.1626	0.0264	88.1985	11.8015
L Anterior	-0.3525	0.635	0.0188	0.1475	0.1463	0.0214	93.3976	6.6024
LL Posterior	-0.428	0.6779	0.0657	0.1523	0.1374	0.0189	89.7631	10.2369
LR Posterior	-0.5317	0.8432	0.0475	0.2059	0.2003	0.0401	80.6156	19.3844
Full Upper	-0.3536	0.7137	0.0423	0.1236	0.1161	0.0135	94.3975	5.6025
U Anterior	-0.2961	0.3295	0.0248	0.0775	0.0734	0.0054	98.6465	1.3535
UL Posterior	-0.2383	1.2315	0.1554	0.3107	0.269	0.0724	78.2684	21.7316
UR Posterior	-0.3536	0.5433	0.0288	0.1142	0.1105	0.0122	94.1491	5.8509
Full Lower	-0.4958	0.5652	0.0421	0.131	0.1241	0.0154	94.985	5.015
L Anterior	-0.4036	0.448	-0.014	0.1213	0.1205	0.0145	96.9602	3.0398
LL Posterior	-0.2142	0.5786	0.0852	0.1385	0.1092	0.0119	93.8307	6.1693
LR Posterior	-0.4958	0.5444	0.0767	0.1366	0.113	0.0128	94.45	5.55
Full Upper	-0.4303	0.4295	0.0112	0.0853	0.0846	0.0072	98.5985	1.4015
U Anterior	-0.2767	0.2944	0.0065	0.0703	0.07	0.0049	99.7282	0.2718
UL Posterior	-0.4565	0.3514	0.0222	0.0951	0.0925	0.0085	97.2167	2.7833
UR Posterior	-0.355	0.5579	0.0222	0.1038	0.1014	0.0103	97.2749	2.7251
Full Upper	-0.4539	0.4538	0.036	0.0992	0.0925	0.0086	96.3431	3.6569
U Anterior	-0.2925	0.2908	0.0204	0.0667	0.0635	0.004	99.5803	0.4197
UL Posterior	-0.4188	0.5571	0.0573	0.1228	0.1086	0.0118	94.1346	5.8654
UR Posterior	-0.5521	0.4689	0.0406	0.1341	0.1278	0.0163	91.0007	8.9993
Full Lower	-0.4144	0.415	0.0253	0.0963	0.0929	0.0086	97.0188	2.9812
L Anterior	-0.1989	0.4033	0.0133	0.0968	0.0959	0.0092	97.6879	2.3121
LL Posterior	-0.3192	0.3204	0.029	0.0774	0.0718	0.0052	98.7276	1.2724
LR Posterior	-0.4749	0.5023	0.0407	0.1209	0.1138	0.013	93.7173	6.2827
Full Upper	-0.2882	0.4421	0.0176	0.0871	0.0853	0.0073	97.885	2.115
U Anterior	-0.2787	0.2904	0.0009	0.0687	0.0687	0.0047	99.4512	0.5488
UL Posterior	-0.2882	0.5072	0.0408	0.099	0.0902	0.0081	96.7317	3.2683
UR Posterior	-0.1867	0.6072	0.0307	0.1316	0.1279	0.0164	93.3709	6.6291
Full Lower	-0.8382	0.8451	0.0799	0.1921	0.1747	0.0305	85.1098	14.8902
L Anterior	-0.2573	0.7826	0.125	0.2042	0.1615	0.0261	78.9905	21.0095
LL Posterior	-0.7173	0.7343	0.0509	0.1594	0.151	0.0228	91.2517	8.7483
LR Posterior	-0.8722	0.878	0.0421	0.1878	0.183	0.0335	88.506	11.494
Full Upper	-0.3848	0.6288	0.0544	0.1394	0.1284	0.0165	91.1757	8.8243
U Anterior	-0.3273	0.3275	0.0034	0.0758	0.0757	0.0057	98.3973	1.6027

UL Posterior	-0.2233	0.8569	0.1021	0.2033	0.1758	0.0309	82.7506	17.2494
UR Posterior	-0.2079	0.7907	0.1459	0.2161	0.1594	0.0254	78.6084	21.3916
Full Lower	-0.5028	0.5018	0.0152	0.1174	0.1164	0.0135	93.3305	6.6695
L Anterior	-0.5033	0.4891	-0.0115	0.1224	0.1218	0.0148	92.4667	7.5333
LL Posterior	-0.3621	0.4754	0.031	0.1071	0.1025	0.0105	94.5815	5.4185
LR Posterior	-0.3883	0.5409	0.042	0.1249	0.1176	0.0138	92.8826	7.1174
Full Upper	-0.375	0.7828	0.0546	0.1566	0.1467	0.0215	90.9697	9.0303
U Anterior	-0.2582	0.3675	0.0396	0.089	0.0797	0.0064	98.1491	1.8509
UL Posterior	-0.2848	1.0083	0.0794	0.2201	0.2053	0.0422	83.2346	16.7654
UR Posterior	-0.375	1.0382	0.0822	0.2383	0.2236	0.05	82.3353	17.6647
Full Upper	-0.4167	0.7776	0.0731	0.1616	0.1441	0.0208	89.4673	10.5327
U Anterior	-0.4068	0.4051	0.0058	0.0906	0.0904	0.0082	97.7714	2.2286
UL Posterior	-0.1182	0.7949	0.154	0.2171	0.1531	0.0234	77.9193	22.0807
UR Posterior	-0.1964	1.0396	0.1183	0.2092	0.1725	0.0298	84.8101	15.1899
Full Lower	-1.2319	1.1447	0.0286	0.1968	0.1947	0.0379	87.6984	12.3016
L Anterior	-1.2319	0.9747	0.0894	0.2243	0.2057	0.0423	81.374	18.626
LL Posterior	-0.8181	0.8132	0.0031	0.1334	0.1334	0.0178	93.6152	6.3848
LR Posterior	-1.0275	0.8564	-0.0069	0.1506	0.1504	0.0226	92.8426	7.1574
Full Upper	-0.6853	0.7569	0.093	0.1688	0.1409	0.0199	89.0858	10.9142
U Anterior	-0.203	0.3836	0.0332	0.0948	0.0888	0.0079	97.8998	2.1002
UL Posterior	-0.1247	0.8571	0.1321	0.2025	0.1535	0.0236	85.2336	14.7664
UR Posterior	-0.1469	0.9834	0.1752	0.2583	0.1898	0.036	75.7629	24.2371
Full Lower	-0.3442	0.4614	0.0251	0.0958	0.0924	0.0085	97.5987	2.4013
L Anterior	-0.1928	0.2895	-0.0028	0.0737	0.0736	0.0054	99.9525	0.0475
LL Posterior	-0.3426	0.6443	0.0595	0.1465	0.1339	0.0179	92.1987	7.8013
LR Posterior	-0.26	0.4037	0.0496	0.0884	0.0732	0.0054	97.9668	2.0332
Full Upper	-0.3157	0.4642	0.0019	0.1052	0.1052	0.0111	96.7202	3.2798
U Anterior	-0.232	0.3981	0.0416	0.0918	0.0819	0.0067	97.5446	2.4554
UL Posterior	-0.3157	0.4685	-0.0443	0.1185	0.1099	0.0121	95.6222	4.3778
UR Posterior	-0.2825	0.6026	-0.0134	0.137	0.1364	0.0186	94.0166	5.9834
Full Lower	-0.457	0.4841	0.017	0.1098	0.1084	0.0118	95.4257	4.5743
L Anterior	-0.2273	0.5213	0.074	0.1297	0.1065	0.0113	92.575	7.425
LL Posterior	-0.3142	0.4884	-0.0062	0.1122	0.112	0.0125	96.1914	3.8086
LR Posterior	-0.381	0.3842	-0.0107	0.0887	0.088	0.0077	96.8861	3.1139

Full Upper	-0.8408	0.6452	0.003	0.1625	0.1625	0.0264	88.5768	11.4232
U Anterior	-0.2896	0.5571	0.0532	0.1299	0.1185	0.014	92.0629	7.9371
UL Posterior	-0.7467	0.4606	-0.0957	0.201	0.1767	0.0312	80.6848	19.3152
UR Posterior	-1.4096	1.3229	-0.06	0.2934	0.2872	0.0825	77.6291	22.3709
Full Lower	-0.7539	0.8408	0.0011	0.2032	0.2032	0.0413	81.1816	18.8184
L Anterior	-0.2442	0.7168	0.1259	0.185	0.1355	0.0184	84.3764	15.6236
LL Posterior	-0.7539	0.5777	-0.1117	0.225	0.1954	0.0382	77.372	22.628
LR Posterior	-0.4904	0.7095	-0.0558	0.1823	0.1736	0.0301	85.8526	14.1474
Full Upper	-0.6269	0.6282	0.0585	0.141	0.1283	0.0165	90.9753	9.0247
U Anterior	-0.1579	0.4608	0.0608	0.1198	0.1033	0.0107	93.867	6.133
UL Posterior	-0.2	0.8319	0.0911	0.2111	0.1904	0.0363	82.7165	17.2835
UR Posterior	-0.7591	0.5855	0.0451	0.1665	0.1603	0.0257	86.486	13.514
Full Lower	-0.5217	0.785	0.056	0.1583	0.1481	0.0219	92.3165	7.6835
L Anterior	-0.2689	0.3009	0.0021	0.0915	0.0915	0.0084	99.7686	0.2314
LL Posterior	-0.2386	0.9916	0.1167	0.2267	0.1944	0.0378	85.5916	14.4084
LR Posterior	-0.5217	0.9651	0.1059	0.2237	0.1971	0.0388	83.068	16.932
Full Upper	-0.4613	0.5688	0.0604	0.126	0.1106	0.0122	94.4318	5.5682
U Anterior	-0.1578	0.2554	0.0167	0.0714	0.0694	0.0048	99.9912	0.0088
UL Posterior	-0.1027	0.7763	0.1671	0.2193	0.1419	0.0201	81.5157	18.4843
UR Posterior	-0.4613	0.426	0.0478	0.1295	0.1203	0.0145	92.9693	7.0307

Appendix D: Clinical Retainer Fit Raw Data

Evaluator 1

Patient	Arch	Trad/VBR	Self Retention	Cervical Margin Fit	Stability	Snap Fit	Facial Surface Adaptation	Incisor Seat	Canine Seat	Premolar Seat	1st Molar seat	2nd Molar seat
1	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	2	2	2	1	2	2	2	2	2
1	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	2	2	2	1	2	2	2	2	2
2	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	2	2	2	2	2	2	2	2	2
2	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	2	2	2	2	2	2	2	2	2
3	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	2	2	2	2	2	2	1	1	1
3	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	2	2	2	2	2	2	1	1	1
4	Upper	Trad	2	2	2	2	1	2	2	2	2	2
	Upper	VBR	2	1	2	2	2	1	1	1	1	1
5	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	1	1	1	1	1	1	1	1	1	1
5	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	2	2	2	2	2	2	2	2	2
6	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	1	2	2	1	2	2	2	2	2
6	Lower	Trad	2	2	2	1	2	2	2	2	2	2
	Lower	VBR	2	2	2	1	1	2	2	2	2	2
7	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	2	2	2	2	2	2	2	2	2
8	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	2	2	2	2	2	2	2	2	2
8	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	2	2	2	2	2	2	2	2	2
9	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	2	1	1	2	2	2	2	2	2
9	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	1	2	1	2	2	2	2	2	2
10	Upper	Trad	1	1	1	1	2	2	2	1	1	1
	Upper	VBR	2	2	2	2	2	2	2	2	2	2
11	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	1	2	2	1	2	2	2	2	2
11	Lower	Trad	2	2	2	2	2	2	2	2	2	2

	Lower	VBR	2	2	2	2	2	2	2	2	2	2
12	Upper	Trad	2	1	2	2	2	2	2	2	2	2
	Upper	VBR	2	1	2	2	2	2	2	2	2	2
12	Lower	Trad	2	1	2	2	2	2	2	2	2	2
	Lower	VBR	2	1	2	1	2	2	2	2	2	2
13	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	2	2	2	2	2	2	2	2	2
13	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	2	2	2	2	2	2	2	2	2
14	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	2	2	2	2	2	2	2	2	2
14	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	1	2	2	2	2	2	2	1	1	1
15	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	2	2	2	2	2	2	2	2	2
15	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	2	2	2	2	2	2	2	2	2
16	Upper	Trad	2	2	2	2	2	2	2	2	2	
	Upper	VBR	2	2	2	2	2	2	2	2	1	
16	Lower	Trad	2	2	2	2	2	2	2	2	2	
	Lower	VBR	2	2	2	2	2	2	2	2	1	
17	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	1	2	2	2	2	2	2	2	2

Evaluator 2

Patient	Arch	Trad/VBR	Self Retention	Cervical Margin Fit	Stability	Snap Fit	Facial Surface Adaptation	Incisor Seat	Canine Seat	Premolar Seat	1st Molar seat	2nd Molar seat
1	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	1	1	2	2	1	2	2	2	2	2
1	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	1	1	2	1	2	2	2	2	2	2
2	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	2	2	1	2	2	2	2	2	2
2	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	1	2	1	2	1	2	1	1	1
3	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	1	2	1	1	2	2	1	1	1

3	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	1	2	1	1	2	2	2	2	2
4	Upper	Trad	2	1	2	2	2	2	2	2	2	2
	Upper	VBR	2	1	2	1	1	1	2	1	1	1
5	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	1	2	1	1	1	1	1	1	1
5	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	1	2	2	1	1	1	1	1	1
6	Upper	Trad	2	1	2	2	2	2	2	2	2	2
	Upper	VBR	1	1	1	2	1	2	2	1	1	1
6	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	2	2	2	2	2	2	2	1	0
7	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	2	2	2	2	2	2	2	2	2
8	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	2	2	2	2	2	2	2	2	2
8	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	2	2	2	2	2	2	2	2	2
9	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	1	1	1	1	1	1	1	1	1
9	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	1	1	1	1	1	1	1	1	1
10	Upper	Trad	2	2	1	1	2	2	2	2	1	1
	Upper	VBR	2	1	2	1	2	2	2	2	2	2
11	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	1	2	2	2	2	1	2	2	2
11	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	1	2	2	2	2	2	2	2	2
12	Upper	Trad	2	2	2	2	2	2	1	2	2	2

	Upper	VBR	2	1	2	2	2	2	2	2	2	2
12	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	1	2	2	1	1	1	2	2	2
13	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	1	2	2	1	2	2	2	1	1
13	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	1	2	2	1	2	2	2	1	1
14	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	1	2	2	2	2	2	2	2	2
14	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	2	2	1	1	1	2	2	2	2
15	Upper	Trad	2	2	2	2	2	2	2	2	2	2
	Upper	VBR	2	2	2	2	2	2	2	2	2	2
15	Lower	Trad	2	2	2	2	2	2	2	2	2	2
	Lower	VBR	2	2	2	2	2	2	2	2	2	2
16	Upper	Trad	2	2	2	2	2	2	2	2	2	
	Upper	VBR	1	1	1	1	2	2	2	2	1	
16	Lower	Trad	2	2	2	2	2	2	2	2	2	
	Lower	VBR	2	1	1	2	2	2	2	2	2	
17	Upper	Trad	2	1	2	2	2	1	1	2	2	2
	Upper	VBR	2	1	2	2	2	2	2	2	2	2