5-2015

Evaluating the marginal integrity of lithium disilicate veneers fabricated by digital impressions and CAD/CAM compared to conventional techniques.

Michael C. Guzelian
University of Louisville

EVALUATING THE MARGINAL INTEGRITY OF LITHIUM DISILICATE VENEERS FABRICATED BY DIGITAL IMPRESSIONS AND CAD/CAM COMPARED TO CONVENTIONAL TECHNIQUES

Michael C. Guzelian
B.S., Georgia Institute of Technology, 2012

A Thesis Submitted to the Faculty of the School of Dentistry of the University of Louisville
in Partial Fulfillment of the Requirements
for the Degree of

Master of Science in Oral Biology

Department of Oral Health and Rehabilitation
University of Louisville
Louisville, Kentucky

May 2015

EVALUATING THE MARGINAL INTEGRITY OF LITHIUM DISILICATE VENEERS FABRICATED BY DIGITAL IMPRESSIONS AND CAD/CAM COMPARED TO CONVENTIONAL TECHNIQUES

Michael C. Guzelian
B.S., Georgia Institute of Technology, 2012

A Thesis Approved on

April 1, 2015

By the following Thesis Committee:

____

Dr. Amirali Zandinejad, DDS, MS
Thesis Director

____

Dr. Michael Metz, DMD, MSD, MS, MBA

____

Dr. Tamer Abdel-Azim, DDS

____

Dr. Donald Demuth, PhD

____

Dr. Douglas Darling, PhD
Program Director

DEDICATION

This dissertation is dedicated to my parents, Charles and Karen Guzelian, and my sister, Krista Guzelian, whose sacrifices for my education, personal development, and well-being have positively shaped my growth as a critical thinker and successful young adult. Their unconditional love and constant support for these endeavors cannot be expressed fully in words.

ACKNOLWEDGEMNTS

I would like to thank my thesis advisor, Dr. Amirali Zandinejad, for his patience, guidance, trust, and encouragement throughout the entire research process. Dr. Zandinejad offers a wealth of knowledge on prosthodontics, clinical dental training, and evidence-based dentistry, and he maintained very high standards in this thesis to produce an exceptional final product. Dr. Zandinejad provided confidence in my abilities that I will succeed in dental school and beyond.

In addition, I would like to thank my thesis committee members: Dr. Tamer Abdel-Azim, for his step-wise clarity during the impressions process and expertise on CAD/CAM applications in dentistry; Dr. Michael Metz, for his high expectations in my degree to yield significant and publishable results; and Dr. Don Demuth, for his willingness to listen and participate in a field outside his own expertise as another prominent, national voice within oral biology.

I would like to thank Dr. Dean Morton for approving a non-specialty graduate student to complete a thesis-based degree within his department, a consideration which included specialty equipment, clinical materials, financial support, and faculty involvement to complete the study.

I would like to thank Dr. Claudio Maldonado for allowing me access to his laboratory for imaging, which included a stereomicroscope and capturing software.

I would like to thank Mr. Younathan Abdia for his counseling of feasible statistical tests within this study and his counseling using statistical software to properly analyze data.

And finally, I would like to thank my Program Director, Dr. Douglas Darling, for allowing me to explore all possible avenues of my Masters degree as a non-conventional graduate student pursuing dentistry. Dr. Darling's consideration included additional coursework and extended time to satisfy all requirements I set out for myself, and I wholeheartedly appreciate his consideration.

ABSTRACT

EVALUATING THE MARGINAL INTEGRITY OF LITHIUM DISILICATE VENEERS FABRICATED WITH DIGITAL IMPRESSIONS AND CAD/CAM COMPARED TO CONVENTIONAL TECHNIQUES

Michael C. Guzelian

April 1, 2015

This *in vitro* study compared marginal gap size in anterior lithium disilicate veneers produced by conventional and digital impressions. One typodont right central incisor was prepared for an all-ceramic cast. Ten conventional veneers were fabricated using Type IV stone, PVS, and IPS e.max press, while ten digital veneers were fabricated using Lava COS (3M ESPE) and IPS e.max CAD/CAM processing and milling. Samples were divided double-blindly, captured at 45X magnification, evaluated at three images per orientation (B-D-M-P), and measured at three distances (largest, smallest, best fit) per image. Data points were entered into SPSS code for one-way and two-way ANOVA, t-testing, Chi square, and odds ratio. Compared to conventional technique, digital veneers recorded greater mean gap distances at all orientations, fewer "good fit" locations, and average gap size ≥ 120 μm. All analysis techniques were statistically significant. *In vivo* follow-up is necessary to justify digital impressions in clinical settings.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF IMAGES

I. INTRODUCTION

All-Ceramic Restorations in Dentistry

The advancement of dental biomaterials and innovative technology creates a promising future for the progression of clinical dentistry. Dental literature agrees that the application of metal crowns remains a viable, reliable, and consistent tooth-replacement strategy for posterior restorations (Waggoner et al., 2006 and Randall et al., 2002). Unlike metal alloys, ceramics are characterized as a non-metallic material containing inorganic components (Rosenblum and Schulman, 1997). Dental ceramics are composed of a particle-filled and glassy outer porcelain material, representing optical properties of enamel and dentin, and a tougher, generally crystalline substructure core (Kelly, 2004). Achieving a quality interface between core substructure and its veneering material presents challenges, since the integration of chemically dissimilar biomaterials to create strong bonding can be diminished during the fabrication process (Culp and McLaren, 2010). With increasing demands for esthetic dentistry in clinical settings, the need for a fracture-resistant, tooth-colored restoration from ceramic seems to be essential.

Clinical Performance of Ceramic Restorations

To succeed in clinical outcomes, the application of ceramic materials in crowns, fixed partial dentures, and veneer restorations requires a precise biological and mechanical consideration to compete with full-cast or ceramo-metal restorations (Conrad et al, 2007). Dental ceramic is influenced by natural stresses within the oral cavity, including flexural, residual and localized stresses (Swain et al., 2014), but the clear advantage for all-ceramic material lies in its esthetic potential (Donovan et al., 2008) and biocompatibility (Lu et al., 2013). Dental literature has frequently supported a consistent clinical performance of all-ceramic restorations compared to partial or full metal restorations. A 2007 systematic review of 34 published articles determined that 93.3% of all-ceramic crowns qualified for 5-year survival, an optimistic percentage similar to 95.6% of 5-year survival rates met for metal-ceramic crowns (Sailer et al., 2007). More recently, molar all-ceramic zirconia restorations exhibited an 86.8% success rate compared to 90.9% in metal-ceramic restorations (Rinke et al., 2012), supporting an earlier study that evaluated positive clinical behavior between all-ceramics and metal-ceramics (Etman et al., 2010). More clinical evaluations verify a promising long-term effect on posterior restorations, where 95.1% of all-ceramic crowns remained replacement-free after 5 years and 92.8% after 10 years, citing core replacement as the primary cause for future repair (Dhima et al., 2012). Despite long-term success, the tendency for chipping in all-ceramic crowns is statistically significant depending on location and tooth type, typically favoring anterior over posterior regions after looking at 5-year fracture rates (Wang et al., 2012).

Full-Coverage to Partial-Coverage Crowns

Full-coverage crowns, which include crowns composed of one material, display superior retention and resistance properties (Shillingburg et al., 2012) and significantly higher survival rates compared to partially-covered metal-ceramic or all-ceramic crowns (Burke et al., 2008). The primary drawback to full-coverage preparations, however, is in its destructive and subtractive method, compromising dentin support and removing excess tooth structure (Guess et al., 2009). Progression to partial coverage crowns enhanced structural integrity through conservative design, resulting in greater bonding, esthetic desire, and minimal tooth reduction (Rappelli et al., 2004 and Broderson, 1994). In promising fashion, partial crown preparation design can potentially restore teeth using ceramic material, performing at 96.7% longevity (Schulte et al, 2005).

Veneer Restorations

Unlike crown coverage restorations, porcelain veneer restorations bond a thin laminate to reduced tooth surfaces using adhesive and resin cement (Peumans et al., 2000). The desired outcome is generally to alter the color, morphology, size, or position of anterior teeth without compromising healthy enamel depth during the reduction (Öztürk et al., 2013). Preparation guidelines for a porcelain veneer require three precise measurements – 0.5 millimeter cervical reduction, 0.7 millimeter midfacial reduction, and 1.5 millimeter incisal reduction (Shillingburg, 2012), guidelines designed to allow proper cementation through conservation of natural enamel (Lin et al., 2012). Recently, it was shown that the optimization of physical properties within resin cement during final preparation contributes to esthetic, clinical, and functional parameters in veneer restorations (Archegas et al., 2011).

Unlike the survival rates before re-intervention for full-coverage and partial-coverage crown restorations (Burke et al., 2008), a subsequent veneer study showed that only 53% of porcelain laminate veneers survived without re-intervention after 10 years, while 20% of those replaced-veneers required greater invasion to treat the problem (Burke et al., 2009). In contrast, a longer 16-year follow-up study determined that 304 feldspathic porcelain veneers yielded a 96% survival rate at 5-6 years, 93% at 10-11 years, and 73% from 15-16 years, suggesting a slow, predictable negative trend in survival spanning past a decade (Layton et al., 2007). A recent meta-analysis of veneer longevity suggests that inconsistent clinical outcomes can be traced to differences in experimental methodologies, treatment settings, clinician skill level and proficiency, access to resources, and population pool bias (Layton et al., 2012). Similar to other all-ceramic therapies, poor long-term outcomes may originate from a non-uniform adhesion complex, inflammatory gingiva response due to biomaterials, and abrasive angle contacts from faulty geometry reduction (Peumans et al., 2000).

Marginal Integrity

Shillingburg proposes that tooth preparation is based on five principles: structure preservation, retention and resistance, structural durability, marginal integrity, and periodontium preservation. These qualitative and quantitative principles work in conjunction to influence long-term clinical performance for restorations (Shillingburg, 2012).

Holmes et al. defined the first consistent definition of marginal fit as the absolute marginal discrepancy, calculated from over and under-extending casting margins, by way of vertical and horizontal discrepancy, seating discrepancy, and misfit measured at points between casting surface and the tooth (Holmes et al., 1989). Established dental literature supports clinically acceptable marginal integrity from 40 to 120 μm (McLean et al., 1971, Bader et al., 1991, Sulaiman et al, 1997), with 120 μm considered the "maximum, tolerable marginal opening" for tooth preparations (Contrepois et al., 2013). Unacceptable or inadequate marginal fits (typically wider than 120 μm) can shorten the longevity of a restoration due to greater cement film exposure (Yucel et al., 2013). In the modern definition, marginal integrity is considered the "absolute vertical distance between a finish line of the prepared tooth and the margins of a fabricated veneer" (Aboushelib et al., 2012), the acceptable degree of marginal exposure between a restorative veneer and its tooth of interest determines long-term durability (Celick et al., 2002). Internal marginal adaptation, an extension to marginal fit measurements, evaluates the relative thickness of resin cement lying directly underneath a veneer restoration and contributes to clinical outcomes (Aboushelib et al., 2012).

Given that marginal integrity is a significant criterion in long-term clinical success, a greater cement film (Almeida et al., 2013) results in several complications; including mechanical defects, discoloration and decay (Aboushelib et al., 2012), luting agent dissolution (Colpani et al., 2013 and Baig et al., 2010); microleakage and plaque accumulation (Contrepois et al., 2013, Beuer et al., 2010, and Bergenholtz et al., 1982); increased recurrent caries incidence (Felden et al., 2000); and pulpal inflammation (Bader et al., 1991). While some literature suggests a higher accuracy of marginal fit in metal-ceramic over all-ceramic restorations, others suggest negligible differences between these restoration types (Pneumans et al. 2000). It is paramount to the clinician to minimize any inherent risk by delivering high-quality, close proximal marginal and internal fit between restorations and their abutment (Almeida et al., 2013), and veneers are not an exemption.

Marginal accuracy is linked to design and manufacturing considerations of ceramic veneers (Toh et al., 1987), commonly from interplay between a substructure core and its veneer material. In a failure pattern study evaluating three veneering materials on marginal fit and fracture resistance of an alumina core, Fahmy determined that a larger marginal gap between a core and its veneer presented a significantly decreased fracture resistance (Fahmy, 2011). With marginal performance in mind, dental researchers are progressing towards a substantial, fixed crystalline material manufactured for anterior or posterior ceramic restorations.

Elastomer versus Scanner Impressions

Conventional impressions, which commonly involve elastomer such as vinyl polysiloxane and polyether, are considered cost-effective and resilient materials in practice for restorative dentistry (Jamani et al., 1989, Clancy et al., 1983, and Endo et al., 2006). Elastomers are characterized on their aqueous properties: (1) aqueous elastomers, which are dimensionally unstable, include agar, a reverse hydrocolloid poured immediately, and alginate, an irreversible hydrocolloid poured within ten minutes; and (2) non-aqueous elastomers, namely polyvinyl siloxanes (PVS), which exhibit moderate strength through dimensional stability, elastic recovery, and adequate contact angles on maxillary and mandibular arches.

Distinct advantages exist in the application of conventional PVS impression material, including minimal and simple equipment, relatively inexpensive full-arch materials, high accuracy press, and a straightforward clinical technique well-established in dental communities (Christensen, 2008). Despite these benefits, conventional impressions exhibit deficiencies, including messy preparations with debris material, potential patient discomfort during impressing, and air bubbles causing cast-pour errors (Christensen, 2008). Even with the emergence of alternative technology to overcome conventional impressions, most active clinicians are content using traditional impressions and feel little pressure to change these techniques serving their patients (Christensen, 2009).

Digital impressions, accomplished without the required cast-pouring or die trimming, reflect distinct benefits over conventional methods, including eliminated mess and clean-up procedures, improved patient comfort, and rapid transfer to laboratory locations for milling (Christensen, 2009). In a study assessing efficiency outcomes between conventional and digital impressions, Lee et al. reported a lower preparation, working, and re-take time in digital impressions and lower level of difficulty conducting digital impressions for implant services (Lee et el., 2012). A subsequent study by Lee documented the favorable perception and rapidly growing preference for digital impressions in dental student communities compared to active clinicians, suggesting a clear transition for newfound practitioners utilizing modern digital techniques (Lee et al., 2013). In a controlled clinical trial comparing a patient's perceived source of stress, attitude, and perception between a standard, polyether arch bite impression and intraoral bite scan, digital impressions were considered the more efficient and comforting treatment plan (Yuzbasioglu et al., 2014).

Conventional Pressing Technique

In 2015, the most common fabrication technique of ceramic restorations still remains the IPS Empress system created by Ivoclar Vivadent. The manufacturer applies a hot-pressing of leucite glass-ceramic designed for single-unit crowns, inlays, onlays, and veneers (El-Mowafy et al., 2002). IPS Empress fabrication is based on the following steps: (1) pre-sintered glass-ceramic ingots, (2) a mold wax-up by lost-wax procedure, (3) the ceramic placed in an automatic furnace to achieve viscous plasticity, (4) complete contour wax by phosphate-bonded dentin investment, (5) dentin-shading of the ingot, and (6) application of an outer-enamel porcelain layer to match optical properties (Dong et al., 1992 and Holand et al., 2000). Ivoclar Vivadent introduced IPS Empress II which incorporated a 60% lithium-silicate glass ceramic (Sorensen et al., 1998) that outperformed leucite-reinforced porcelain in fracture toughness and flexural strength tests (Holand et al., 2000).

Lithium Disilicate

Lithium disilicate, considered a special subset of particle-filled glasses, presents a crystalline filler engineered as a monolithic, high-strength (360-400 MPa) ceramic crown which (1) does not require a secondary layering or adhesive cementation bonds, (2) withstands normal masticatory forces, and (3) exhibits greater fracture resistance and flexural strength compared to pressed zirconia (Kim et al., 2014). In 2005, Ivoclar Vivadent introduced IPS e.max lithium disilicate as a full-contour, monolithic ceramic press technique exhibiting the following physical properties: optimal flexural strength (360-400 MPa), high fracture toughness (2-3 MPa), and high thermal shock resistance, all while eliminating the dissimilar material interface previously observed in zirconia (Tysowski, 2009). In manufacturing centers, IPS e.max press applies traditional lithium disilicate, composed of quartz, lithium dioxide, phosphor oxide, alumina, potassium oxide, and other components, through a series of melting, cooling, nucleating, and crystallizing of a glass ingot to produce a 70% volume of needle-like crystals. Before the crystallization per volume is achieved, the company provides a wide variety of glass ingots with contrasting opacity and translucency levels to satisfy a clinician's esthetic outcome – high opacity (HO), medium opacity (MO), low translucency (LT), and high translucency (HT) are the primary selections for anterior restorations (Ivoclar Vivadent, 2009).

Dental literature suggests of clear transition in heat-pressing protocols to the use of monolithic lithium disilicate over bilayered or reinforced biomaterials. A recent study evaluating fracture resistance by static loading determined that monolithically pressed lithium disilicate crowns exhibited greater fracture resistance over zirconia/fluroapatite pressed-over crowns (Altamimi et al., 2014). Likewise, the microstructure of lithium disilicate glass ceramic is shown to outperform feldspathic and leucite-reinforced materials with respect to resistance of crack formation and propagation during *in vitro* wear testing (Etman, 2009).

Lava Chairside Oral Scanner (COS) by 3M ESPE

With respect to intraoral scanners, the Lava COS system utilizes three-dimensional motion technology based on the following principles: (1) capturing images of data in real-time from a single lens measuring depth at different perspectives, (2) measuring out-of-plane coordinates of object points using an off-axis aperture element, and (3) utilizing 24 million generated data points per scan through three overlapping images captured simultaneously (Rohaly et al. 2006 and 3M Technical Data Sheet, 2009).

Logozzo presents a detailed description of the Lava COS scanning process and its digital conversion for manufacturing restorations. An operator must prepare the area of interest by dusting all surface contacts using titanium dioxide powder, a substance which highlight contrast mediums on the gingiva surface. Within the allotted time per arch, an operator uses the wand hand pulsating a blue light, a process known as “stripe scanning,” to scan the desired region at all proximal contacts. If any coverage areas are insufficient, an operator can re-scan the errors via rotation and magnification of the model on screen to detect irregularities. After the arches are complete, a closed-bite jaw record, or maximum intercuspal position, is required to properly articulate maxillary and mandibular positions for registration (Logozzo et al., 2011). Next, the operator transmits these final images via a wireless prescription to a laboratory technician, who virtually customizes margins to digitally cut a die, mark the margins, and generate a stereolithography (SLA) file. When an SLA model is articulated with all operative, opposing, and bite scans, the file is sent back to the laboratory technician for the preferred finishing technique, usually heat-pressing or virtual manufacturing (Birnbaum et al., 2009).

Dental literature has established that among competitors within digital scanners and against conventional impression technique, Lava COS is considered a consistent and accurate scanning protocol for restorative services. Schafer determined that the type of digital impression technique utilized *in vitro*, which examined iTero, cara TRIOS, CEREC AC, and Lava COS, significantly influences the marginal fit of lithium disilicate partial crowns (Schaefer et al., 2014). Van der Meer et al. evaluated the intraoral scanning accuracy between CEREC, iTero, and Lava COS systems for a master model made from high-precision polyether-ether-ketone cylinders. Lava COS exhibited the least scanning variance for spatial and angulation measurements between these cylinder centers and generated the fewest mean distance errors; this literature advocated it as the most accurate digital workflow for implant restorations (van der Meer et al., 2012). Ender et al. compared the accuracy (trueness and precision) of an *in vitro* full arch model fabricated by Lava COS and Cerec AC Bluecam protocols compared to conventional impressions. After data records were superimposed on the master model between impressions groups, the accuracy of digitally impressed arches were statistically similar to conventional impressions (Ender et al., 2011). Güth et al. tested the *in vitro* accuracy of a titanium, four-unit fixed dental prosthesis reference model by (1) direct Lava COS data capturing, (2) digitizing a polyether impressions, and (3) indirect gypsum cast scanning using Lava Scan ST. After datasets were aligned with a reference dataset, 3D divergences and positive or negative deviations were calculated. A direct digitalization using Lava COS showed a statistically significant and higher accuracy to the reference model compared to conventional impressions and indirect digitalization (Güth et al., 2013).

Computer-Aided Design and Manufacturing (CAD/CAM) System

The emergence of Lava Chairside Oral Scanner (3M ESPE), CEREC (Sirona), and iTero (Cadent) has enhanced the speed and quality of synergistic collaboration between chairside dental impressions and laboratory milling. Using an accurate digital impression with proper occlusion, clinicians can fabricate all-ceramic restorations by aid of computer-aided design and manufacturing (CAD/CAM), a subtractive technology, and open access systems – a combination which increases technically-sensitive precision for a finished product (Schaefer et al., 2013). The elementary, former digital workflow for CAD/CAM is based the following execution: (1) data acquisition of a tooth's geometry using an intraoral scanning device, (2) data processing into a virtual or physical cast, and (3) manufacturing of the cast in a nearby laboratory or remote production center (Touchstone et al., 2010 and Logozzo et al., 2011). The CAM-processing of the restoration from CAD software is based upon a number of milling axes and path points, offering simple-to-complex spatial directions depending on the complexity designated for geometric restoration. Potential materials utilized in CAD/CAM include metals, resin, silica-based ceramics, infiltration ceramics, and aluminum and yttrium-stabilized oxide blocks (Beuer et al., 2008). The former digital workflow overcomes the challenges for clinicians using a traditional workflow with impressions trays; challenges including mold instability, transport, or packaging, plaster pouring and solidification, delamination, lacerations on margins, and geometrical inconsistencies between plaster model and real teeth (Logozzo et al., 2014).

Beyond its streamlined operational advantages against PVS, CAD/CAM creates the desired flexibility for clinicians to customize dental restorations specific to a patient's need (Noort, 2012). The supplementary role of Chairside Economic Restoration of Esthetics Ceramics (CEREC), combined with CAD/CAM, can generate a scanned tooth surface in three dimensions and manufacture a restoration at a personal dentist's office (Mormann, 2006). A virtual in-office milling produces convenient single-visit restorations, eliminates temporary restorations or repeated procedures, and offers financial flexibility for services that normally require extra appointments (Christensen, 2009).

In combination with monolithic lithium disilicate, increasing *in vitro* evidence proposes a CAD/CAM crown restoration can compete, and possibly outperform, crowns fabricated from bi-layered CAD or layering-pressed techniques. Monolithic lithium disilicate crowns from IPS e.max CAD are shown to withstand mouth-motion fatigue and resist fracture at higher loads over hand-layered-veneered IPS e.max ZirCAD crowns (Guess et al., 2010). In determining the ultimate load to failure and chipping behavior of zirconia-framework crowns veneered by glass-infused lithium disilicate IPS e.max CAD or conventional manual-layering material, CAD/CAM crowns resisted artificial ageing at fractures up to 1600 N, while 87.5% of conventionally-veneered crowns failed during chewing stimulation (Schmitter et al., 2012).

Digital Workflow and Marginal Integrity

The marginal fit of all-ceramic CAD/CAM crowns fabricated from intraoral digital impressions is promising compared to conventional techniques, and contemporary work considers accessible marginal accuracy (AMI) and internal fit (IF) as factors when analyzing the marginal integrity (Holmes et al., 1989). Syrek et al. conducted an *in vivo* double-blind study in 20 patients preparing two zirconia crowns each, one fabricated by silicone two-step putty-wash impressions and the other fabricated by Lava COS. Compared to PVS impressions (71 μm), all-ceramic zirconia crowns subjected to Lava COS (49 μm) demonstrated significantly improved marginal fit, closer interproximal contact quality, and acceptable marginal discrepancy (Syrek et al., 2010). Scotti et al. tested the accuracy of 37 zirconia-ceramic single crowns (anterior and posterior) made by Lava COS for 15 patients requiring a full-coverage restoration. After measuring for marginal and internal fitting values under a stereomicroscope, it was determined that the placement accuracy under clinical conditions was acceptable for Lava COS (Scotti et al., 2011). Seelbach et al. measured all-ceramic zirconia crowns impressed with multiple intraoral acquisition systems – Lava COS, CEREC, and iTero – compared to two-step and one-step putty wash impressions. After measurements were performed via a 3D-coordinate system and assessed at 50 points per crown for local deviations, digital impressions delivered comparable mean internal fit and accessible marginal inaccuracy similar to conventional methods. Lava COS outperformed CEREC with respect to internal fit, an outcome possibly attributed to superior resolution properties during the scanning process (Seelbach et al., 2013).

Despite encouraging progress in the digital workflow for all-ceramic restorations, dental literature indicates that marginal integrity is compromised compared to conventional technique. Anadioti et al. released a study investigating the 3D and 2D marginal fit of lithium disilicate crowns fabricated by (1) PVS/IPS e.max press, (2) PVS/IPS e.max CAD,

(3) Lava COS/IPS e.max press, and (4) Lava COS/IPS e.max CAD. In measuring the marginal integrity using 3D laser-coordination and 2D microscopic measurements at facial-lingual and mesial-distal locations, a conventionally impressed, IPS e.max pressed crown (3D: 48 µm, 2D: 40 µm) produced the most accurate marginal fit. Lava COS/IPS e.max press (3D: 89 µm, 2D: 75 µm) and Lava COS/IPS e.max CAD (3D: 84 µm, 2D: 74 µm) were still clinically acceptable. In a subsequent study with similar group conditions, Anadioti measured the internal fit, again using 3D laser-coordination at axial walls and on the occlusal surface. Lava COS/IPS e.max press crowns (211 µm) produced the least accurate and largest average internal gaps compared to a PVS-pressed crown (111 µm) and Lava/CAD crown (145 µm), suggesting that a complete or partial digital workflow does not satisfy internal fit standards (Anadioti et al., 2014 and 2015).

Logozzo et al. presented the concepts of rapid digital workflow in 2014, a transition in working principles allowing a clinician who owns an intraoral scanner to conveniently mill restorations in-office within minutes. These advances provide clinicians significant advantages over former digital workflow, including (1) database updates for existing patient profiles, (2) periodic restorations which optimize marginal preparations long-term, (3) simulations of surgical interventions on a digital model for cases requiring invasive treatment, and (4) streamlined esthetic outcomes desired by patients (Logozzo et al., 2014). In 2015, the application of CAD/CAM for fabricating definitive veneers is evolving through virtual esthetic treatment that facilitates feedback between clinician, patient, and laboratory technician (Lin et al., 2015). Zandinejad et al. released a clinical case report detailing the costs and benefits of a comprehensive, cast-free digital workflow for anterior, maxillary laminate veneers. In considering CAD design software as an alternative to traditional pressing restorations, a digital workflow presented customizable, provisional veneers that optimized final shape, contour, and shading in a patient's restoration – an advantage that comes at a cost, including higher laboratory fees, increased chair time and additional appointments (Zandinejad et al., 2015). Considering the fast-growing, favorable perception of digital impressions within the dental student community (Lee et al., 2013), the impact of a cast-free digital workflow on clinical parameters for all-ceramic, anterior veneers is presently unexplored *in vitro*.

Unlike the recent progress investigating digital techniques on all-ceramic crowns, no conclusive evidence exists to suggest that digitally impressed, anterior laminate veneers from CAD/CAM virtual design yield superior or inferior marginal fit differences against conventional approaches. Evaluating marginal fit, through *in vitro* and clinical studies, would justify the contribution of digitally impressed veneers within esthetic anterior restorations, offer clinicians greater insight into the risks and benefits of digitally designed restorations, and provide a logical alternative to conventional impressions in dentistry.

Research Objectives

The primary purpose of this study was to evaluate and compare the marginal integrity of anterior lithium disilicate veneers fabricated from a digital workflow (Lava COS and CAD/CAM) compared to conventional technique (PVS impressions and IPS e.max press). The secondary purpose of this study was to evaluate the gap distance trends of digitally impressed veneers, with respect to a 120 µm clinical threshold, against conventionally impressed veneers. The null hypothesis (H_o) of this study is that the average marginal integrity of digitally impressed veneers exhibited a distance greater than or equal to 120 µm compared to conventionally impressed veneers. The alternative hypothesis (H_A)

is that the average marginal integrity of digitally impressed veneers exhibited a distance less than 120 µm compared to conventionally impressed veneers.

II. MATERIALS AND METHODS

Diagnostic Cast and Veneer Reduction

Columbia dentoform was used as an *in vitro* model (Dentoform M-860, Columbia Dentoform Corporation, Long Island City, NY) to prepare a veneer on maxillary right central incisor (tooth #8). A diagnostic maxillary and mandibular cast was constructed using Jeltrate Regular Set Alginate impression material (Dentsply Caulk, Milford, DE) and Type IV dental stone (Jade stone, WhipMix Corp., Louisville, KY). A reduction guide was fabricated with the cast using Clear Temporary Splint material (Buffalo Dental Mfg Co Inc., Syssoset, NY).

Maxillary right central incisor tooth #8 was prepared using guidelines recommended as follows: preparation depth 1.5 mm incisally, 0.5 mm cervically, and 0.7 mm facially using round-ended diamond cutting instruments (Braessler USA, Savannah, GA).

Custom Tray Fabrication

Ten (10) custom trays were made of the diagnostic casts using Triad TruTray Custom Tray Material (Dentsply, York, PA). To block out undercuts in the jade stone cast, TruWax baseplate wax (Dentsply, York, PA) was heated in boiling water, pressed over the typodont cast, and reduced using a scalpel blade number 20 (Miltex, York, PA). Following baseplate placement, Triad TruTray material was draped and pressed over the maxillary arch, trimmed with scalpel, and set in a light curing unit (Triad 2000 Dental, Dentsply, York, PA) for eight minutes. After curing, a carbide acrylic bur (Faskut Carbide Cutter, 216C, Dentsply, York, PA), polishing brush (Polishing Brushes-Coarse, Medium, and Fine, Dentsply, York, PA), pumice and pumice wheel (CL-85 Pumice, Whip Mix, Louisville, KY) was used to smooth edges and finish the custom tray.

Conventional Veneers

Using ten fabricated custom trays, ten conventional impressions were taken of the prepared tooth on a selected typodont using light and heavy body polyvinyl siloxane (PVS) as a one-step impression (Dentsply, Aquasil Ultra, York, PA) following manufacturer instruction. Conventional impressions were sent to a commercial dental lab for Type IV die stone pouring and casting. Ten monolithic, ceramic veneers were created from a traditional IPS e.max hot-press technique: (1) low translucency, lithium disilicate glass ingots waxed up to full contour; (2) melting, cooling, nucleation, and crystallization steps of glass ingots; and (3) pressed microstructure crystals resulting in 70% lithium disilicate veneers (LT IPS e.max Press, Vita A2; Ivoclar Vivadent). Samples were delivered back for marginal integrity testing.

Digital Veneers

Ten digital impressions were taken of dentoform on (1) the maxillary arch holding a reduced veneer model, (2) the opposing mandibular arch, and (3) a closed-jaw record using a Lava COS scanner (Software Version 3.0.2, 3M ESPE, St. Paul, MN) according to manufacturer's recommendations. Titanium dioxide ESPE Lava scanpowder (3M ESPE, St. Paul, MN) was lightly administered as a contrast medium on both arches of the dentoform and closed-jaw record before each subsequent scan. Complete scan coverage was achieved in the allotted time assigned for each sample. The intraoral scanner overlapped all information obtained from maxillary, mandibular, and closed-bite scans to form a complete bite registration. Files were then sent electronically to a commercial dental laboratory (Roy Dental Laboratory, New Albany, IN) for virtual preparation and design of laminate veneer margins. The designed veneers were sent to milling centers for post-processing and veneer fabrication using IPS e.max computer-aided design and manufacturing (CAD/CAM) with lithium disilicate glass-ceramic block (LT e.max CAD, Vita A2; Ivoclar Vivadent). Milled and processed restorations were delivered back for marginal integrity testing.

Marginal Gap Measurement

All 20 veneers fabricated by conventional and digital impressions were divided in two designations, Group 1 and Group 2, in double-blind fashion by a supervisor prosthodontist. Four separate baseplate wax moldings were created to allow resting position in four orientations. These wax moldings were shaped and sculpted at equal heights to allow the clearest magnification and light contrast of each sample holding a ceramic veneer covering. All veneers were positioned on each indented baseplate wax molding for buccal, distal, mesial, and palatal orientations. The marginal gap was measured under 45X magnification using a stereomicroscope attached to a microscopic camera and captured by Windows Movie Maker software.

Three images were recorded per orientation: (1) at the mid-point initially marked by a prosthodontist’s penmark and one full image frame (2a) above and (3a) below the pen marking or one full image frame (2b) right and (3b) left of the pen marking. Depending on the orientation designation (B, D, M, P), the mid-point image was labeled “1”, frames above and below were labeled “2” and “3”, and frames to the right and left were labeled “2” and “3”. Before capture, each ceramic veneer placed upon the resting model was fitted as tightly as possible by the operator according to gravity. Specimens were not cemented for any measurement, and no operator hand-pressure was applied to the model and its ceramic sample at any moment during image acquisition. All images were recorded in one session under normal laboratory conditions.

Two images were not recorded due to unreadable gap distances on the stereomicroscope: the third image in Sample 2 of Group 1 at the buccal region recorded a gap distance wider than the 45X frame, while Sample 7 in Group 2 at the palatal region recorded a maximum pressed gap distance between the veneer and the sample.

Image Analysis

Relative gap distance was calibrated using a standard 1 mm (1000 μm) scale captured at 45X. Using free ImageJ software downloaded for Window 7, the calibrated scale was standardized to a certain pixilation distance by aligning gap distance with respect to pixel length (467 pixels = 1 μm). Three gap distance lines were drawn and filled per captured image: (1) largest possible value, (2) smallest possible value, and (3) the operator’s best fit representation of the distance. From these three measurements, mean gap size ($\overline{X}$) and standard deviation (S.D.) was calculated and displayed per image per orientation per sample for Groups 1 and 2.

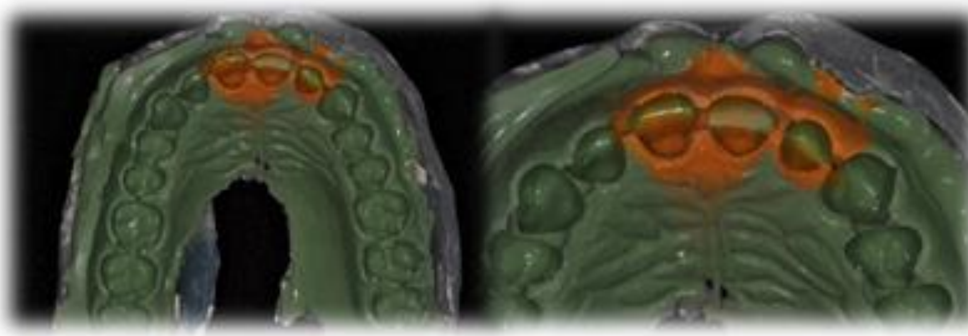
Image acquisition resulted in 119 images for Group 1, 119 images for Group 2, and 738 data points in total for analysis. The mean, standard deviation, best fit, smallest, and largest values were inputted and saved into a Microsoft Excel spreadsheet, and data was transferred and entered into free SPS Statistics software (Version 17.0) downloaded on Windows 7. All calculation entry into SPSS code occurred by guidance of a biostatistician.

NOTE: An analysis of variance comparison between the mean margin and best fit margin was generated to determine the least biased metric for successive calculations. The average gap exhibited greater statistical significance in two-way and one-way ANOVA calculations over the operator's best fit margin. Therefore, the **average** (mean) gap, which accounted for the largest, smallest, and best fit value, was utilized in all calculations requiring the mean statistic.

Reference Images

(1) An *in vitro* diagnostic cast of the maxillary right central incisor. The ceramic cast was prepared 1.5 mm incisally, 0.5 mm cervically, and 0.7 mm facially.

(2) Final custom trays of the diagnostic cast. Custom trays were prepared using Triad TruTray material and TruWax baseplate wax, cured for dryness, and polished using a carbide acrylic bur and pumice wheel.

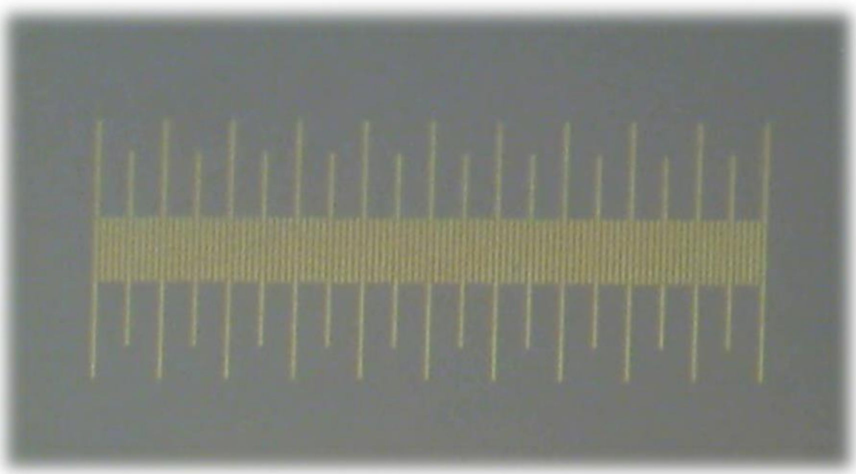


(3) Light and heavy body PVS impressions of the typodont. Conventional impressions were sent for stone casting and high translucency IPS e.max press.

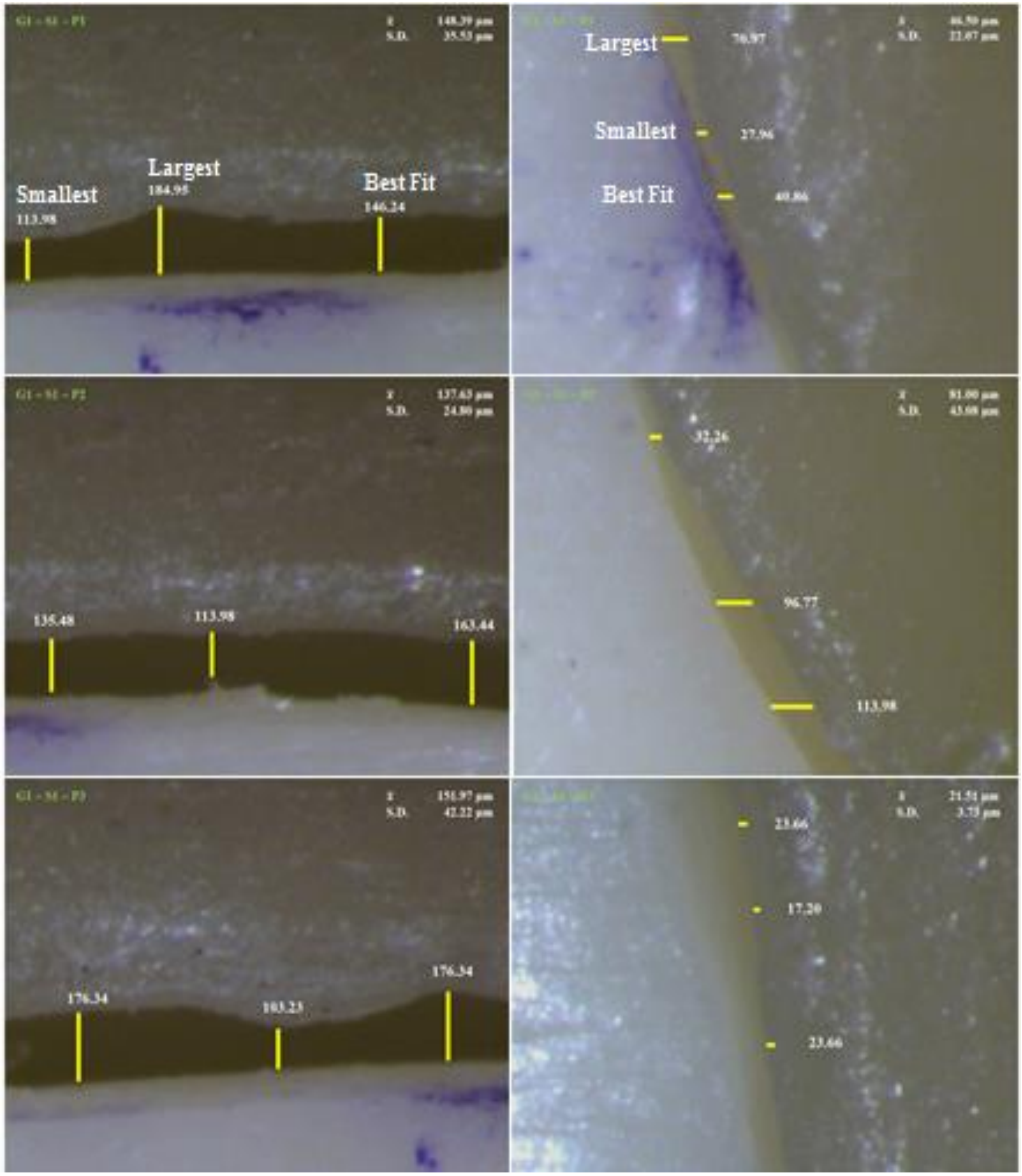
(4) Complete arch digital impressions (Lava COS) of the dentoform. Impressed veneers were sent for virtual IPS e.max CAD/CAM milling and processing.

(5) Marginal integrity testing using a stereomicrosope (45X). All veneers were fitted on the cast using wax moldings for normal resting position during imaging.

(6) Orientations of fitted veneers in buccal (B), palatal (P), mesial (M), distal (D) position. Specimens were not cemented for any measurement.



(7) Calibrated scale indicating gap distance (1 mm = 1000 µm) at 45X.
ImageJ standardized gap distance with respect to pixel length (467 pixels = 1 µm).



(8) Calculated gap distance using three image frames per orientation. Largest, smallest, and best fit values shown. Mean gap size and standard deviation displayed.

Buccal | Palatal Mid-point, one full image frame right and left of pen marking.

Mesial | Distal Mid-point, one full frame above and below pen marking.

III. STATISTICAL ANALYSIS

Summary statistics, which included the mean, standard deviation, maximum, minimum, and number of samples, were generated for gap measures (µm) stratified by impression technique and location. All recorded images were utilized in the generation of this table. Average gap measures were measured (1) between digital and conventional impressions, with subsequent outliers and (2) between impression technique and their locations, accounting for ± 2 standard error bars.

Summary statistics for the mean gap measures (µm) per sample were generated and graphed comparing all image positions and penmark positions (P1, M1, D1, and B1). The smallest mean gap measure (µm) at individual positions was tabulated and graphed for all ten samples per impression technique.

The frequency of mean gap cutoffs by impression technique was calculated using two distance thresholds at ≥ 120 µm and < 120 µm. With respect to these cutoffs, the mean frequency was displayed in numerical tally and percentage format for (1) digital, (2) conventional, and (3) digital + conventional conditions.

Analysis of Variance (ANOVA)

A repeated measures mixed-effects (RMME) model was utilized to calculate two-way analysis of variance (ANOVA) between groups and groups and their locations. Fixed effects included impression technique and location, while random effects included the sample. An additional covariance term for repeated measures included location (orientation) to determine significant differences between impression techniques.

The RMME model was defined in the following form: $\boldsymbol{y_{mean}} = \boldsymbol{\mu} + \boldsymbol{\alpha_i} + \boldsymbol{\beta_j} + (\boldsymbol{\alpha\beta})_{\boldsymbol{ij}}$, where **μ** was the overall mean, **α** was the main effect of groups, **β** was the main effect of positions, and **αβ** was the interaction effect between groups and positions. The source, sum of squares, degree of freedom, mean square, F value, and significance ($\alpha = 0.05$) was calculated to determine if a location effect exists on impression technique differences. If significant ($p < 0.05$), the impression technique effect was analyzed separately with location by testing contrasts within the interaction model.

One-way analysis of variance (ANOVA) within individual groups and their positions was calculated. The model was defined in the following form: $\boldsymbol{y_{mean}} = \boldsymbol{\mu} + \boldsymbol{\alpha_i}$, where **μ** is the overall mean and **α** was the main effect of position. The source, sum of squares, degree of freedom, mean square, F value, and significance ($\alpha = 0.05$) was calculated to determine whether there is a location effect on individual impression techniques.

T-Test

A t-test was conducted on both groups to (1) determine whether the means of impression techniques were statistically significant and (2) accept or reject the study's null hypothesis. The null hypothesis (H_o) stated that digitally impressed veneers exhibited an average gap distance ≥ 120 μm compared to conventionally impressed veneers, while the alternative hypothesis (H_A) stated that digitally impressed veneers exhibited an average gap distance < 120 μm compared to conventionally impressed veneers. Statistical significance ($\alpha = 0.05$) was calculated from t-values for each impression technique. If significant ($p < 0.05$), the null hypothesis was rejected and the alternative hypothesis was accepted. If not significant ($p > 0.05$), the null hypothesis was not rejected and the alternative hypothesis could not be accepted.

Chi Square Test

Pearson's Chi Square test was calculated to determine (1) degree of significance and (2) whether the frequency distribution within a certain event (gap variance) observed in each sample was consistent with a particular theoretical distribution (impression technique). A 2 x 2 table was generated between impression technique and its binary marginal gap using distance cutoffs ≥ 120 μm and < 120 μm. The χ^2 statistic value generated a p-value significance term. If significant ($p < 0.05$), observed differences between categorical data arose by chance and significant association existed between an impression technique and its gap. If not significant ($p > 0.05$), observed differences between categorical data did not arise by chance and there was insignificant association between an impression technique and its gap.

Odds Ratio

The odds ratio measured effect size and strength of association between two binary distance cutoffs ≥ 120 μm and < 120 μm. The 2 x 2 table generated an odd-ratio (OR) statistic value and corresponding p-value significance between impression techniques. If significant ($p < 0.05$), the presence or absence of property A (≥ 120 μm) was closely associated with the presence or absence of property B (< 120 μm) in a given group. If not significant, ($p > 0.05$), the presence or absence of property A (≥ 120 μm) was not closely associated with the presence or absence of property B (< 120 μm) in a given group.

IV. RESULTS

The mean marginal gap measurements within digital and conventional impressions were statistically significant between impression techniques and all locations.

A summary of two-way ANOVA for average gap ($\bar{X}$) and best fit gap size between impression technique and their positions is depicted in **Table 1**. Compared to the best fit, the mean measurement was (1) equally significant at all images per position and (2) more significant at penmark locations between positions ($p = 0.025$) and groups and their positions ($p = 0.000$). A summary of one-way ANOVA in **Table 2** compared digital and conventional groups separately at all images per position, generating a similar trend. The average gap was as significant ($p = 0.000$) for digital impressions and more significant ($p = 0.004$) for conventional impressions than the best fit measurement.

Overall mean gap measures (μm) by impression technique are depicted in **Table 3** and **Table 4** at all positions and mid-point penmark positions. At all positions, digital impressions recorded an overall average gap size of 148.8 μm, while conventional impressions recorded an overall average gap size of 103.6 μm, a distance difference of approximately 45 μm. At penmark positions, digital impressions recorded an overall average gap size of 135.9 μm, while conventional impressions recorded an overall average gap size of 95.8, a distance difference of approximately 40 μm.

Compared to conventional impressions, digital impressions exhibited greater mean gap distances at all orientations.

Figure 1 graphically displays the overall mean gap measure for digital and conventional samples at all positions. Digital impressions, despite larger overall gap size, produced only one outlier value at 380.7 μm within all ranges of sample distances. In contrast, conventional impressions produced eight outliers through its sample set with extremes spanning 307-464 μm. **Figure 3** and **Figure 4** graphically displays average mean gap (μm) measures at all positions and penmark positions by impression technique for each sample. Digital impressions, on average, exhibited larger mean gap distances at all orientations compared to conventional impressions.

As a clinical indicator, digital impressions reported fewer "good fit" locations and gap frequencies.

A summary of average gap measures (μm) by impression technique and individual location is depicted in **Table 5** and graphically in **Figure 2**. In digital impressions, the average gap size in microns for palatal, buccal, mesial, and distal measuring locations were 215.9 (± 74.9), 130.9 (± 50.6), 116.8 (± 91.9), and 130.9 (± 81.8). In conventional impressions, the average gap size in microns for palatal, buccal, mesial, and distal measuring locations were 71.3 (± 109.4), 57.0 (± 25.2), 117.0 (± 107.5), and 168.2 (± 85.4). The smallest overall mean gap was reported at the mesial position (116.8 μm) for digital impressions and at the buccal position (57.0 μm) at conventional impressions. Using a gap distance less than 120 μm as an indicator of good fit, digital impressions only reported one average good fit at the mesial location, whereas conventional impressions reported three average good fits at palatal, buccal, and mesial locations.

A frequency of mean gap cutoffs by impression technique for digital impressions, conventional impressions, and digital + conventional impressions is displayed in **Table 6**. Using gap cutoffs of ≥ 120 µm and < 120 µm, digital groups reported 55% ≥ 120 µm and 44.5% < 120 µm, while conventional groups reported 27.7% ≥ 120 µm and 72.3% < 120 µm. Tallied together, digital plus conventional impressions reported 41.8% ≥ 120 µm and 58.2% < 120 µm.

Compared to conventional veneers, digitally impressed veneers underperformed at the smallest reported mean gap measures.

The smallest mean gap measure (µm) at each position across all samples by impression technique is depicted in **Table 7.** In digital impressions, the smallest mean gap measure across all samples was reported at the mid-point mesial penmark at 77.6 µm. In conventional impressions, the smallest mean gap measure across all samples was reported at the upper buccal mark at 48.63 µm and mid-point buccal penmark at 49.4 µm. The smallest mean gap measures (µm) across all samples at mid-buccal (D: 132.4, C: 49.4, Δ_{Gap} = 83.0), mid-desial (D: 119.6, C: 170.5, Δ_{Gap} = 50.9), mid-mesial (D: 77.6, C: 95.8, Δ_{Gap} = 18.1), and mid-palatal (D: 213.8, C: 67.5, Δ_{Gap} = 146.3) penmarks is displayed in **Table 8**. The largest mean gap differential between groups was observed at mid-palatal (146.3 µm) locations.

With respect to impression technique and location, digital and conventional impressions were statistically significant between groups and within groups.

Two-way analysis of variance of mean gap measures by impression technique and location was depicted in **Table 9**. At all images per position, the main effects of groups (p

= 0.000), positions ($p = 0.016$), and between groups and their positions ($p = 0.000$) were statistically significant at $\alpha = 0.05$ level of significance. At mid-buccal, mid-distal, mid-palatal, and mid-mesial penmarks, the main effects of groups ($p = 0.023$), positions ($p = 0.025$), and between groups and their positions ($p = 0.000$) were statistically significant at $\alpha = 0.05$ level of significance. One-way analysis of variance of mean gap measures by impression technique was depicted in **Table 10** using positions as a source. At all images per position, both digital impressions ($p = 0.000$) and conventional impressions ($p = 0.004$) were statistically significant at $\alpha = 0.05$ level of significance.

The null hypothesis was not rejected for digital impressions, whereas the alternative hypothesis was accepted for conventional impressions.

A t-test of the null hypothesis (H_o: $\mu \geq 120$) and alternative hypothesis (H_1: $\mu < 120$) by impression technique is depicted in **Table 11**. Digital impressions ($t = 3.686$, $p = 0.990$) were not statistically significant from the null hypothesis, and $H_o = \mu m \geq 120$ was not rejected. Conventional impressions ($t = -1.820$, $p = 0.035$) were statistically significant from the null hypothesis, and $H_o = \mu m \geq 120$ was rejected. The alternative hypothesis ($H_1 = \mu m < 120$) was accepted for conventional impressions.

Compared to conventional impressions, digital impressions were three times more likely to exhibit gap distances greater than 120 µm.

Pearson's Chi Square test using gap cutoffs (≥ 120 µm and < 120 µm) by impression technique is displayed in **Table 12**. Pearson's Chi Square test reported $\chi^2 = 14.77$. Odds ratio reported a 3.040 score with 95% CI and $p < 0.05$. The odds of gap distances ≥ 120 μm were approximately 300% more likely to occur in digital impressions compared to conventional impressions, and this result was statistically significant.

V. TABLES & FIGURES

Table 1. Two-Way ANOVA of Impression Technique and Location between Average and Best Fit Gap Measures

		Average	Best Fit
Interaction Method	Source	P Value	
All Images Per Position	Group	0.000	0.000
	Positions	0.016	0.016
	Group*Position	0.000	0.000
P1 – B1 – M1 – D1	Group	0.023	0.017
	Positions	0.025	0.031
	Group*Position	0.000	0.000

Table 2. One-Way ANOVA of Impression Technique between Average and Best Fit Gap Measures

			Average	Best Fit
Group	Interaction Method	Source	P Value	
Digital	All Images Per Position	Positions	0.000	0.000
Conventional	All Images Per Position	Positions	0.004	0.006

No discernable difference found between the mean gap and best fit gap.
All proceeding calculations are based on the **mean gap measurement** per image.

Table 3. Summary Statistics of Mean Gap Measures (µm) between All Positions and Penmark Positions

Sample	All Positions		Penmark Positions	
	Digital	Conventional	Digital	Conventional
1	74.84	109.96	66.46	101.75
2	240.35	114.48	203.25	112.48
3	131.76	96.21	133.92	96.58
4	112.78	77.16	109.26	79.20
5	80.38	100.87	75.48	91.77
6	198.43	93.80	189.33	93.39
7	115.03	82.48	106.89	64.11
8	218.75	78.34	180.46	55.11
9	116.46	213.61	104.48	213.15
10	207.04	68.20	189.42	51.00

Table 4. Overall Mean Gap Measures (µm) by Impression Technique at All Positions and Penmark Positions

	Overall Mean Gap (µm)	
Impression Technique	All Positions	Penmark Positions
Digital	148.8	135.9
Conventional	103.7	95.8

Table 5. Summary Statistics of Gap Measures (µm) by Impression Technique and Location

Impression Technique	Location	N	Mean Gap (µm)	SD	Min	Max
Digital	Palatal	30	215.9	74.9	108.7	339.7
	Buccal	29	130.9	50.6	43.7	243.4
	Mesial	30	116.8	91.9	27.2	380.7
	Distal	30	130.9	81.8	21.5	320.4
Conventional	Palatal	29	71.3	109.4	15.1	464.2
	Buccal	30	57.0	25.2	24.4	112.0
	Mesial	30	117.0	107.5	16.5	409.4
	Distal	30	168.2	85.4	22.2	330.4

Table 6. Frequency of Mean Gap Cutoffs by Impression Technique

Group	Gap Cutoff	Mean Frequency (%)
Digital	≥ 120	66(55.5)
	< 120	53(44.5)
Conventional	≥ 120	33(27.7)
	< 120	86(72.3)
Digital + Conventional	≥ 120	100(41.8)
	< 120	139(58.2)

Table 7. Summary Statistics of Smallest Mean Gap Measures (µm) at Each Position

Position	Sample Size	Digital	Conventional
B1	10	132.48	49.46
B2	10	148.59	73.03
B3	10	109.67	48.63
D1	10	119.62	170.56
D2	10	179.10	155.56
D3	10	94.09	178.57
M1	10	77.63	95.80
M2	10	158.01	114.91
M3	10	114.96	140.91
P1	10	213.84	67.58
P2	10	214.51	78.66
P3	9	219.39	67.37
All Positions	119	148.82	103.69

Table 8. Summary Statistics of Smallest Mean Gap Measures (µm) at Penmark Positions

Position	Sample Size	Digital	Conventional	Δ_{Gap}
B1	10	132.48	49.46	83.02
D1	10	119.62	170.56	50.94
M1	10	77.63	95.80	18.17
P1	10	213.84	67.58	146.26

Table 9. Two-Way ANOVA Mean Gap Measures by Impression Technique and Location

Interaction Method	Source	F Value	P Value
All Images Per Position	Group Positions Group*Position	17.486 2.181 4.428	0.000 0.016 0.000
P1 – B1 – M1 – D1	Group Positions Group*Position	5.407 3.306 6.969	0.023 0.025 0.000

Table 10. One-Way ANOVA Mean Gap Measures by Impression Technique

Group	Interaction Method	Source	F Value	P Value
Digital	All Images Per Position	Positions	4.280	0.000
Conventional	All Images Per Position	Positions	2.679	0.004

Table 11. T-Test of Null and Alternative Hypothesis by Impression Technique

Group	Hypothesis	T Value	P Value	Reject H_o?
Digital	H_o: $\mu \geq 120$ H_1: $\mu < 120$	3.686	0.990	No
Conventional	H_o: $\mu \geq 120$ H_1: $\mu < 120$	-1.820	0.035	Yes

Table 12. Pearson's Chi Square and Odds Ratio by Impression Technique

Gap Cutoff			
Group	≥ 120	< 120	Total
Digital	49 (a)	42 (b)	91
Conventional	33 (c)	86 (d)	119
Total	83	127	210

Method	Statistic Value	P Value
χ^2	14.776	0.000
Odds Ratio	3.040	0.000

Figure 1. Average Gap (µm) Measures by Impression Technique

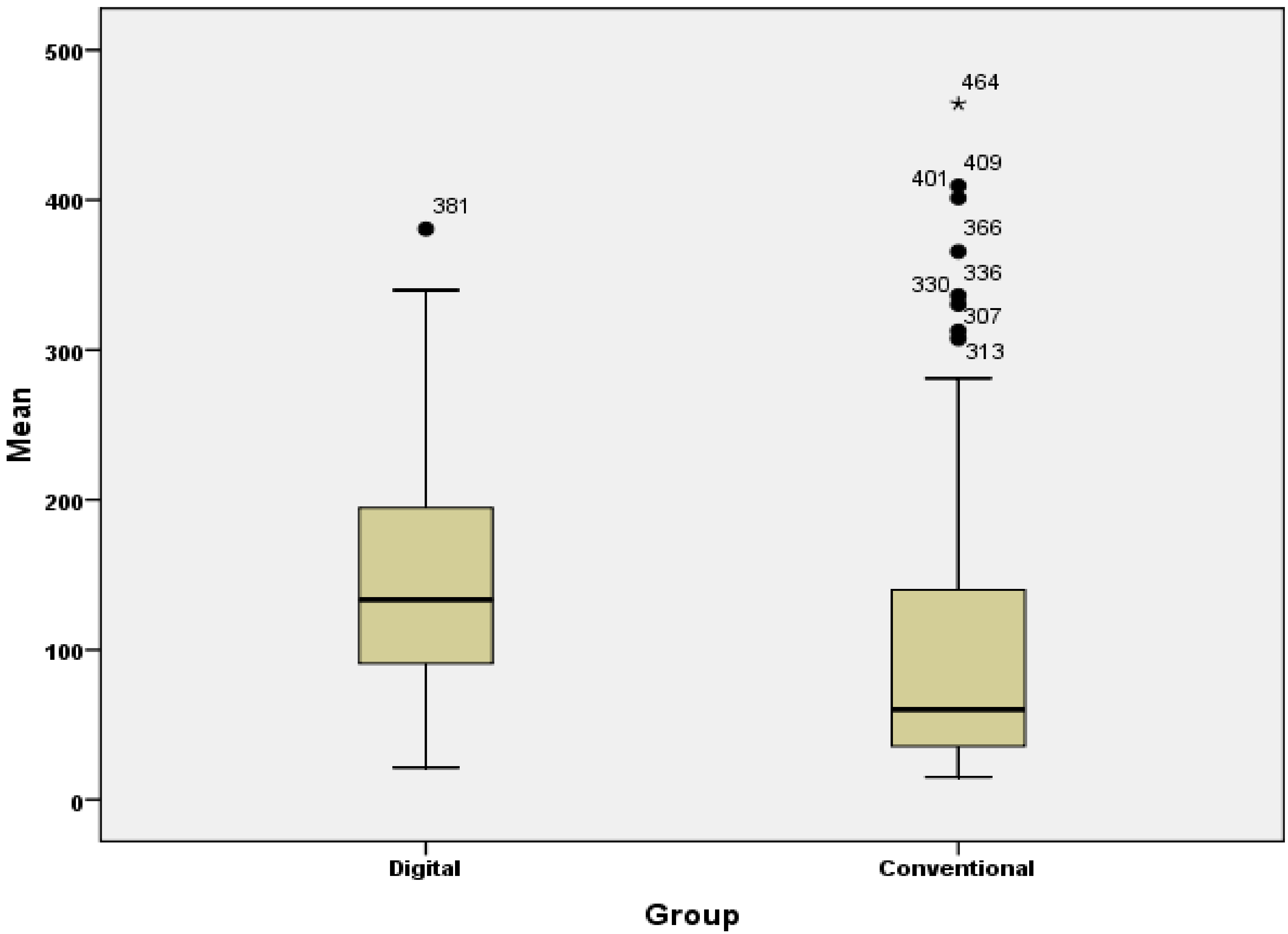
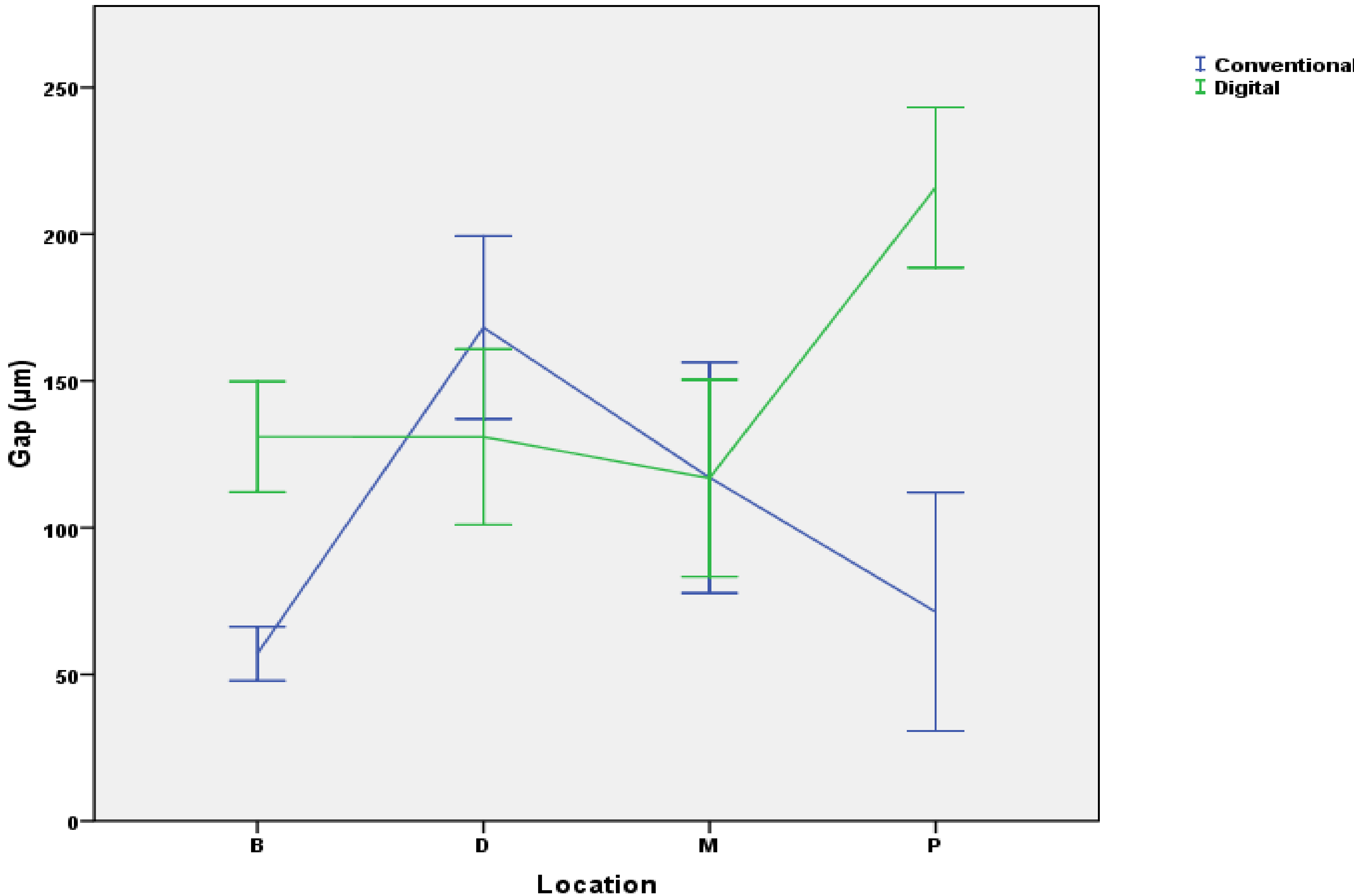


Figure 2. Average Gap (µm) Measures ± 2 SE Bars by Impression Technique and Location



Average Gap Measures ± 2 Standard Error Bars

Figure 3. Average Mean Gap (µm) Measures at All Positions by Impression Technique

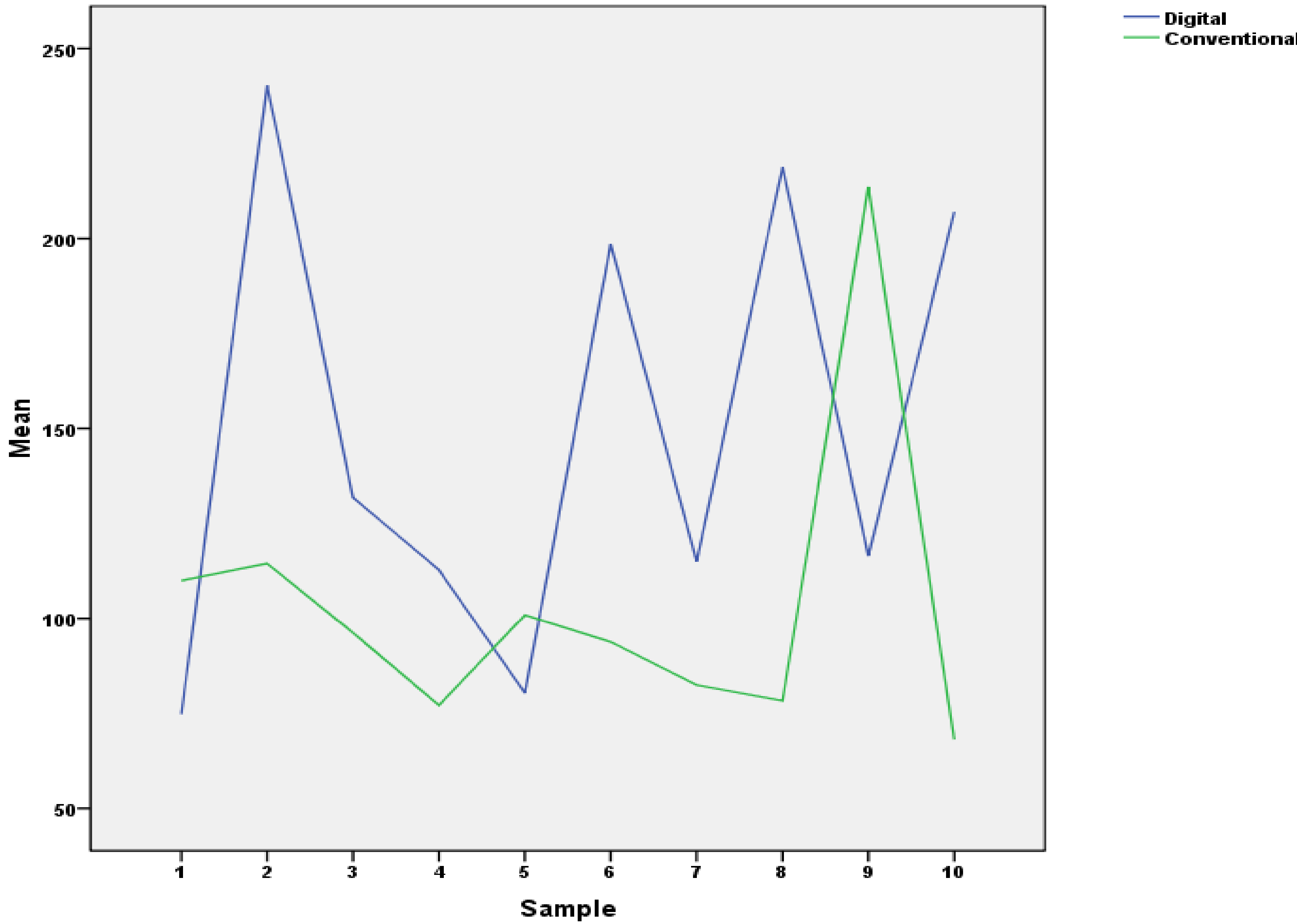
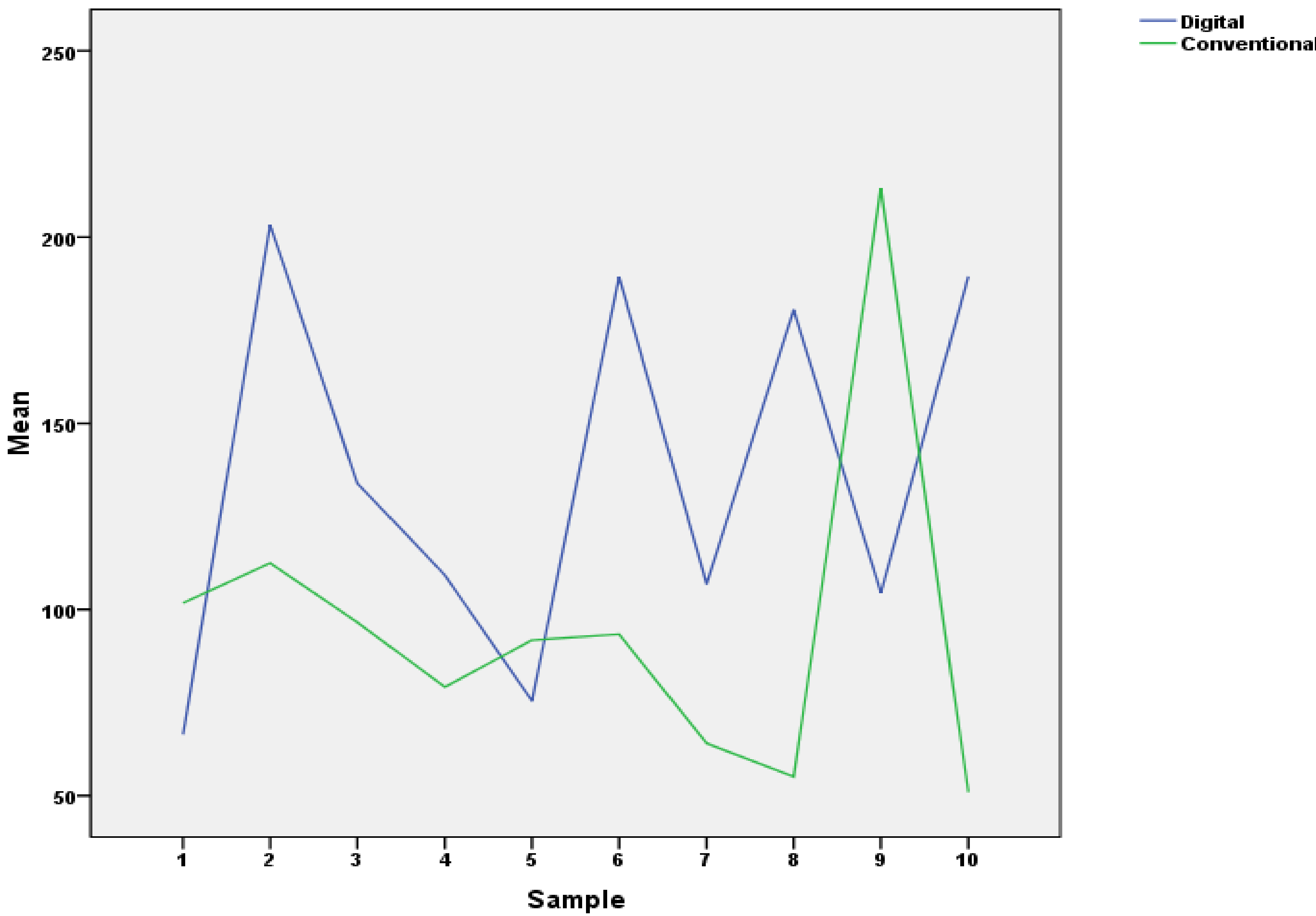


Figure 4. Average Mean Gap (µm) Measures at Penmark Positions by Impression Technique



VI. DISCUSSION

Within the possible limitations of this study, digitally impressed, virtually designed veneers exhibited statistically significant, larger marginal gap compared to conventionally impressed veneers. Using 120 µm as the maximum and acceptable clinical indicator, digital impressions, in conjunction with computer-aided designed and computer-assisted manufacturing, were shown *in vitro* to display inferior marginal fit when compared to conventional technique. The null hypothesis, stating digitally impressed veneers would exhibit an average marginal gap greater than or equal to 120 µm, could not be rejected.

An effort was made in creating the most effective, standardized *in vitro* model to measure accuracy in the laboratory. Veneers manufactured from both impressions were blindly grouped and marked in numbers by the mentor without any prior communication to the operator. Ideal standardization in experimental design and execution was aimed at eliminating as many potential variances and biases during the image acquisition process and statistical analysis. All images were recorded in a single laboratory sessions using the same microscopic set-up to eliminate variances in lighting, magnification, or resolution clarity.

Beyond the original mid-point positions at buccal, distal, palatal, and mesial locations, the veneer's orientation was measured in two additional areas surrounding the proximity of that penmark. This approach yielded three images per orientation per sample and ultimately produced a similar average gap trend at all positions versus penmark positions. Added locations for measurement reinforced the power sample, enhanced an impression's strength of significance, and compounded association between impression technique and its gap outcome. With the exception of two images recording unreadable gap distances out of frame or too tightly pressed against the veneer, all images and data points were utilized in analyzing impression techniques.

Preliminary images displayed mild gap inconsistencies across an image and in observing the smallest and largest gap scores. Thus, it was deemed appropriate to test whether the mean or operator's best fit would most accurately eliminate gap discrepancies and ideally represent gap distance within each sample. Before data analysis, the statistical significance between the mean, utilizing the largest and smallest value, and the operator's best fit margin, reflecting the most consistent gap distance, was compared for all recorded images. For all statistical analysis measures, the mean gap measurement per image was utilized in lieu of the best fit margin. However, it is safe to assume that any statistically significant results generated in this study could be replicated using the operator's best fit marginal score – the significance ($p < 0.05$) for two-way and one-way ANOVA between impression technique and gap outcome were observed in either approach.

As an *in vitro* model, digitally impressed, virtually designed, and milled ceramic veneers exhibited inferior marginal gap against conventional samples by deviating significantly from a clinical gap cutoff. The overall mean gap in digitally impressed veneers exceeded the 120 μm threshold at all frameshift images and lone penmark positions. Digital samples displayed a gap distance 45 μm and 40 μm greater than conventional samples at all positions and penmark positions, respectively.

Inferior margins within digital samples arose at all measured orientations besides the mesial location, which barely fulfilled the theoretical clinical threshold. In contrast, conventionally impressed veneers performed significantly under 120 µm at three orientations, the one exception being the distal location. Digital veneers, while less marginally accurate, were collectively very precise – only one digital outlier value existed in the entire study, compared to multiple outliers observed within conventional samples with noticeable extremes. This behavior lends credence to the idea that intraoral scanners, despite inferior accuracy for anterior veneers in an *in vitro* study, can reliably duplicate a consistent (albeit larger) gap distance for *in vitro* restorations.

The palatal orientation was the most inaccurate marginal gap displayed within digital impressions, yielding 96 µm above the gap threshold. This inaccuracy can be attributed to the difficulty in which a Lava COS scanner acquired and captured data points at the palatal position on the dentoform. Conventionally impressed veneers significantly outperformed digital samples at the palatal and buccal orientation, an anticipated outcome for PVS material pressing tightly on sides adjacent to the palate or inside the cheek.

Changes in gap distance at the mid-point penmark between impression techniques offered a unique perspective on the intraoral scanning coverage of a veneer model. Digitally impressed veneers underperformed against conventional samples at the smallest observed mid-buccal and mid-palatal positions by 83 µm and 146 µm, respectively. However, digital veneers outperformed conventional veneers at the smallest observed mid-distal and mid-mesial positions by 51 µm and 18 µm. This behavior suggests that digitally impressed veneers *in vitro* can be reliably fit at mid-points toward the arch midline.

Variance analysis and t-testing effectively supported the statistically significant difference required to accept or reject the study's null hypothesis. Since digitally impressed veneers exhibited an average marginal gap greater than or equal to 120 µm, the null hypothesis could not be rejected for digital samples. On the contrary, the null hypothesis was rejected for conventional impressions, and the alternative hypothesis that conventionally impressed veneers exhibited an average marginal gap less than 120 μm was accepted.

Based on results from a consistent and thorough experimental design, the frequency distribution within a certain event, gap variance, was strongly associated with a theoretical distribution, fabrication technique, in all samples. Any observed trends in marginal gap between impression techniques were not affected by external, confounding variables beyond operator control. This finding is noteworthy, considering dental literature implementing *in vitro* models often decrease their study's value by producing outcomes influenced by outward factors such as room conditions or skillset factors such as imprecise measurement. Additionally, while the odds ratio alone would not singularly suffice to indicate strength of association, it further supplemented the presence or absence of a particular gap outcome within impression groups. Digitally impressed veneers were approximately three times more likely to exhibit the presence of a marginal distance greater than or equal to 120 μm in the absence of a marginal distance less than 120 μm.

Two minor limitations existed in this study. First, the baseplate wax indentations for each resting position accounted for only forces of gravity after the ceramic veneer was placed. This proved to be difficult in measuring samples at certain orientations, particularly in veneers not seated as tightly as possible without additional finger pressure, which created omissions – one measurement in palatal region for conventional samples due to the veneer pressing so tightly against the sample, another in the buccal region for digital samples due to the veneer falling out of frame. Second, in taking digital impressions, titanium dioxide

ESPE Lava scanpowder was required to optimize scan coverage by contrasting surface medium, but its administration did not guarantee that unexposed margins could be properly acquired within a time limit. The influence of scanning powder on precision is currently unexplored; although the Lava COS algorithm created real-time images by overlapping data points, any miniscule coverage errors resulting from unreached areas scored a larger gap distance and influenced inaccurate milling. However, these limitations were both beyond operator control and should not serve as a deterrent to the statistically significant results produced between groups.

To consider these findings as a concrete indication for the inferior quality of digitally impressed, virtually designed, and milled veneers is impossible to conclude with certainty. The digital samples in this study followed three central steps differing from conventional technique, which included (1) an intraoral scanner used by an operator rather than material pressed against a tooth surface, (2) electronically transmitted data scans for virtual design of veneers instead of a wax-up to full contour, and (3) milling of a final restoration at a remote production center in lieu of investment and pressing of ceramic by a technician. Virtual-to-manufacturing limitations are common when sharp, abrasive diamond-cutting instruments become compromised from heavy, previous usage, causing marginal cheapening of ceramic material. Since veneers demand a scrupulous geometric reduction, any shortcoming in these manufacturing steps affected the delivered marginal integrity of digital casts.

Optimal margins from digital design closely correlate with the competency of a laboratory technician operating this milling equipment. Tsitrou et al. addressed the limitations of machining by investigating a dental material's chipping factor with respect to its brittleness index; in evaluating composite material (Paradigm MZ100), feldpsathic (VITA MKII), leucite reinforced glass ceramic (ProCAD), and lithium silicate glass ceramic (IPS e.max CAD), lithium silicate glass ceramic exhibited the highest brittleness index and the greatest chipping factor – an indicator more likely to produce inferior marginal indicators during the milling process (Tsitrou et al., 2007). Giannetopoulos et al. assessed the average chipping factors between lithium disilicate IPS e.max CAD copings of CEREC inEos and EVEREST systems based on differing bevel angles. Only CEREC software was shown to significantly produce a greater chipping factor from a 60-degree bevel compared to lower angles (30-degree and 0-degree bevels, respectively). However, this observation is only partially supported, suggesting that (1) subtractive methods between CAD/CAM systems are inconsistent and (2) finish line preparation with acute beveling potentially disrupts marginal integrity and longevity (Giannetopoulos et al., 2010). Anadioti found that lithium disilicate crowns fabricated from Lava COS/IPS e.max CAD (73 µm) exhibited statistically comparable mean marginal gap to PVS/IPS e.max CAD technique (76 µm), indicating that either impression can be reliably applied in a clinical setting when virtual milling is the final manufacturing consideration. However, when comparing Lava COS/IPS e.max CAD with PVS/IPS e.max press (39 µm), a digitally-impressed, virtually-designed crown still underperformed in marginal gap against complete conventional technique (Anadioti et al., 2014). These findings support the results in this veneer study, suggesting that a digital workflow requires substantial preparation, design, and milling improvements to compete with a conventional workflow involving PVS materials. Moreover, these factors bring to attention the possible, evolving definition of "good fit" for CAD/CAM restorations and whether the clinical limit should be elevated to more properly validate clinical outcomes for the anterior region.

Aside from machining limitations, a cast-free, digital workflow for restorations inherently restricts fine detailing and surface techniques from a laboratory technician, limits thickness and shading metrics, and demands a steeper learning curve against standard hot-pressing or feldspathic-layering methods (Zandinejad et al., 2015). Over time, computer-assisted design and manufacturing will be improved as digital protocols become streamlined and commercially popular in practice for prosthodontists to utilize in anterior restorations. With respect to this study, the reproducibility and dimensional repeatability of a maxillary right central incisor with Lava COS is promising and reliable *in vitro*. Balakrishnama et al. produced 25 intraoral scans of one prepared anterior and one posterior copper die, analyzing scans for dimensional surface area deviations. Lava COS exhibited anterior repeatability ≤ 5.8 μm and posterior repeatability ≤ 10.9 μm, displaying clinical acceptability for crown or bridge restorations (Balakrishnama et al., 2009). While there is confidence that both experimental groups omitted confounding variables from tooth preparation, scanning design, and milling, successive *in vitro* veneers studies would aid in advancing our results.

As the digital workflow evolves, the impact of proper faculty instruction on graduate dental students is vital to the transition of digital impressions and CAD/CAM software in aesthetic dentistry. Supervised prosthodontic clinics should reflect CAD/CAM as an alternative workflow to conventional wax-up and not as a direct replacement when considering possible treatment plans in high-esthetic restorations (Zandinejad et al., 2015). Obtaining satisfactory data points with an intraoral scanner, particularly from rotating the scanning wand in multiple orientations, presents advanced training beyond normal skillsets acquiring interproximal margins from PVS impression materials (Abdel-Azim et al., 2015). At the very least, an improved efficiency workflow can justify introducing contemporary technology to pre-doctoral students during faculty instruction. The significantly reduced delivery time in scanning a preparation, opposing dentition, and its closed-jaw bite registration should serve as a promising starting point to its usage in clinical settings.

Recent trends in technology suggest that modern prosthodontists support digital scanners in practice and can effectively compensate for any potential setbacks seating a digitally impressed ceramic restoration in the posterior or anterior region. Regardless of shortcomings presented with digital workflow, a marginal gap larger than 120 µm, while deemed unacceptable in dental academia, may not be very critical to long-term, restorative success in veneers when using adhesive resin cements. Literature indicates that Cercon zirconia crowns against conventional IPS Empress II ceramic and metal crowns exhibit comparable margins within 120 µm acceptability – a distance variance that may be shortened using greater adhesive luting-agent viscosity, corrected luting space settings on CAD/CAM systems (Baig et al., 2010), and an acceptable modulus of elasticity during masticatory forces (Shahrbaf et al., 2014). Brawek et al. compared the marginal fit of digitally-impressed Lava COS (51 µm) and CEREC (81 µm) posterior crowns, stating that gap discrepancies from intraoral scanner competitors may not be clinically relevant if fitting occurs under 120 µm (Brawek et al., 2013). However, dental literature does not address (1) whether a maximum, tolerable limit of 120 µm in veneers can be offset with compensatory techniques, (2) whether optimal function is maintained in veneers deviating above 120 μm, and (3) if wider margins recorded from digital workflow ultimately hinders long-term clinical outcome in anterior restorations.

In terms of all-ceramic veneers, future *in vitro* avenues include testing the marginal and internal fit for conventional/press, conventional/CAD, digital/press, and digital/CAD conditions in lithium disilicate veneers. Determining an interaction, if any, between combinations of impression material and fabrication technique would offer clinicians greater flexibility in customizing anterior restorations independent of fixed protocols, potentially melding a hybrid workflow. Another consideration would include using digital shape scanning and processing (DSSP) to virtually measure 3D and 2D margins on a master die with processing software in lieu of a manual stereomicroscope by an operator.

This *in vitro* study requires future *in vivo* follow-up to compare the longevity of veneer restorations fabricated from digital work flow – digital scanning, virtual design, and milling – in comparison to conventional technique. These considerations, along with the findings in this study, can create a powerful argument towards the progression of digital design in practice and academia.

VII. CONCLUSIONS

Within the possible limitations of this study, the following conclusions were drawn:

1. Digitally impressed, virtually designed, and milled lithium disilicate veneers exhibited significantly larger marginal gaps than conventionally impressed, pressed veneers.
2. Digitally impressed, virtually designed, and milled lithium disilicate veneers exhibited statistically significant margins greater than or equal to 120 µm compared to conventionally impressed, pressed veneers.

Using 120 µm as the maximum and acceptable clinical indicator, digital samples were shown *in vitro* to display inferior marginal fit when compared to conventional samples. The null hypothesis, stating cast-free, fabricated veneers would exhibit an average marginal gap greater than or equal to 120 µm, could not be rejected.

VIII. CLINICAL APPLICATIONS

This *in vitro* study does not account for any obstacles or limitations faced within an *in vivo* environment. Factors such as salivary flow, impression placement, treatment complications and adverse biomaterial response, and patient compliance may affect a statistically significant marginal fit between impression techniques. Using 120 μm as a clinical indicator, a cast-free technique *in vitro* to fabricate anterior lithium disilicate veneers would not be considered a suitable alternative to conventional technique. Future *in vivo* studies should be conducted to more precisely evaluate the results of this study and in a clinical application.

REFERENCES

All-Ceramic Restorations in Dentistry

Waggoner, WF. "Anterior Crowns for Primary Anterior Teeth: An Evidence Based Assessment of the Literature." *European Archives of Pediatric Dentistry* 1.2 (2006): 53-57.

Randall, Ros C. "Preformed Metal Crowns for Primary and Permanent Molar Teeth: Review of the Literature." *Pediatric Dentistry* 24.5 (2002): 489-500.

Rosenblum, MA, and A. Schulman. "A Review of All-ceramic Restorations." *Journal of the American Dental Association* 128.3 (1997): 297-307.

Kelly, J. Robert. "Dental Ceramics: Current Thinking and Trends." *Dental Clinics of North America* 48.2 (2004): 513-30.

Culp L, McLaren EA. Lithium disilicate: The restorative material of multiple options. *Compend Contin Educ Dent*. 31.9 2010:716-20, 722, 724-5.

Clinical Performance of Ceramic Restorations

Conrad, H., W. Seong, and I. Pesun. "Current Ceramic Materials and Systems with Clinical Recommendations: A Systematic Review." *The Journal of Prosthetic Dentistry* 98.5 (2007): 389-404.

Swain, Michael V. "Impact of Oral Fluids on Dental Ceramics: What Is the Clinical Relevance?" *Dental Materials* 30.1 (2014): 33-42.

Donovan, TE. "Factors Essential for Successful All-Ceramic Restorations." *Journal of the American Dental Association* 139 (2008): 14S-18S.

Lu, Chenglin, Raoro Wang, Schuangshuang Mao, Dwayne Arola, and Dongsheng Zhang. "Reduction of Load-bearing Capacity of All-ceramic Crowns Due to Cement Aging." *Journal of the Mechanical Behavior of Biomedical Materials* 17 (2013): 56-65.

Sailer I, Fehér A, Filser F, et al. 2007. Five-year clinical results of zirconia frameworks for posterior fixed partial dentures. *Introductory Journal of Prosthodontics*. 20(4):383-388.

Rinke, S., S. Schafer, K. Lange, N. Gersdorff, and M. Roediger. "Practice-based Clinical Evaluation of Metal–ceramic and Zirconia Molar Crowns: 3-year Results." *Journal of Oral Rehabilitation* 40.3 (2012): 228-37.

Etman, Maged K., and M.J. Woolford. "Three-year Clinical Evaluation of Two Ceramic Crown Systems: A Preliminary Study." *The Journal of Prosthetic Dentistry* 103.2 (2010): 80-90.

Dhima, Matilda, Vladimira Paulosova, Alan Carr, Kevin Rieck, Christine Lohse, and Thomas Salinas. "Practice-based Clinical Evaluation of Ceramic Single Crowns after at Least Five Years." *The Journal of Prosthetic Dentistry* (2013).

Wang, X., D. Fan, M. Swain, and K. Zhao. "A Systematic Review of All-ceramic Crowns: Clinical Fracture Rates in Relation to Restored Tooth Type." *International Journal of Prosthodontics* 25.5 (2012): 441-50.

Full-Coverage to Partial-Coverage Crowns

Burke, F., and P. Lucarotti. "Ten-year Outcome of Crowns Placed within the General Dental Services in England and Wales." *Journal of Dentistry* 37.1 (2009): 12-24.

Guess, Petra C., Joerg R. Strub, Niclas Steinhart, Martin Wolkewitz, and Christian F.J. Stappert. "All-ceramic Partial Coverage Restorations—Midterm Results of a 5-year Prospective Clinical Splitmouth Study." *Journal of Dentistry* 37.8 (2009): 627-637.

Rappelli, G., E. Coccia, and A. Putignano. "Restoration of Anterior Teeth with Indirect Composite Partial Coverage Crowns: A Clinical Report." *The Journal of Prosthetic Dentistry* 92.6 (2004): 519-22.

Schulte, A., A. Vockler, and R. Reinhardt. "Longevity of Ceramic Inlays and Onlays Luted with a Solely Light-curing Composite Resin." *Journal of Dentistry* 33.5 (2005): 433-442.

Veneer Restorations

Peumans, Michael, B Van Meerbeek, P. Lambrechts, and G. Vanherle. "Porcelain Veneers: A Review of the Literature." *Journal of Dentistry* 28.3 (2000): 163-177.

Öztürk, Elif, Yu-Chih Chiang, Erdal Coşgun, Şükran Bolay, Reinhard Hickel, and Nicoleta Ilie. "Effect of Resin Shades on Opacity of Ceramic Veneers and Polymerization Efficiency through Ceramics." *Journal of Dentistry* 41 (2013): E8-E14.

Öztürk, Elif, Şükran Bolay, Reinhard Hickel, and Nicoleta Ilie. "Shear Bond Strength of Porcelain Laminate Veneers to Enamel, Dentine and Enamel–dentine Complex Bonded with Different Adhesive Luting Systems." *Journal of Dentistry* 41.2 (2013): 97-105.

Archegas, Lucí Regina Panka, Andrea Freire, Sergio Vieira, Danilo Biazzetto De Menezes Caldas, and Evelise Machado Souza. "Colour Stability and Opacity of Resin Cements and Flowable Composites for Ceramic Veneer Luting after Accelerated Ageing." *Journal of Dentistry* 39.11 (2011): 804-810.

Burke, F.J.T., and P.S.K. Lucarotti. "Ten-year Outcome of Porcelain Laminate Veneers Placed within the General Dental Services in England and Wales." *Journal of Dentistry* 37.1 (2009): 31-38.

Layton, Danielle, and Terry Walton. "An Up to 16-Year Prospective Study of 304 Porcelain Veneers." *The International Journal of Prosthodontics* 20 (2007): 389-96.

Layton, Danielle, Michael Clarke, and Terry Walton. "A Systematic Review and Meta-Analysis of the Survival of Feldspathtic Porcelain Veneers Over 5 and 10 Years." *The International Journal of Prosthodontics* 25 (2012): 590-603.

Marginal Integrity

Shillingburg, Herbert T. Fundamentals of Fixed Prosthodontics. Chicago: Quintessence Pub., 2012.

Holmes, J. Robert, Stephen C. Bayne, Gene A. Holland, and William D. Sulik. "Considerations in Measurement of Marginal Fit." *The Journal of Prosthetic Dentistry* 62.4 (1989): 405-408.

McLean, J. W., and Fraunhofer Von. "The Estimation of Cement Film Thickness by an in Vivo Technique." *British Dental Journal* 131.3 (1971): 107-111.

Bader, James D., R. Gary Rozier, Walter T. Mcfall, and Diane L. Ramsey. "Effect of Crown Margins on Periodontal Conditions in Regularly Attending Patients." *The Journal of Prosthetic Dentistry* 65.1 (1991): 75-79.

Sulaiman, Frankie, John Chai, Lee M. Jameson, and Wayne T. Wozniak. "A Comparison of the Marginal Fit of In-Ceram, IPS Empress, and Procera Crowns." *The International Journal of Prosthodontics* 10 (1997): 478-484.

Contrepois, Mathieu, Arnaud Soenen, Michel Bartala, and Odile Laviole. "Marginal Adaptation of Ceramic Crowns: A Systematic Review." *The Journal of Prosthetic Dentistry* 110.6 (2013): 447-454.e10.

Yucel, Munir Tolga, Filiz Aykent, and Mustafa Cihat Avunduk. "In vitro Evaluation of the Marginal Fit of Different All-ceramic Crowns." *Journal of Dental Sciences* 8.3 (2013): 225-230.

Aboushelib, Moustafa Nabil, Waleed Abdelmeguid Elmahy, and Mohammed Hamed Ghazy. "Internal Adaptation, Marginal Accuracy and Microleakage of a Pressable versus a Machinable Ceramic Laminate Veneers." *Journal of Dentistry* 40.8 (2012): 670-677.

Celik, Cigdem, and Deniz Gemalmaz. "Comparison of Marginal Integrity of Ceramic and Composite Veneer Restorations Luted with Two Different Resin Agents: An In Vitro Study." *The International Journal of Prosthodontics* 15 (2002): 59-64.

Almeida e Silva, Junio, Kurt Erdelt, Daniel Edelhoff, Elito Araujo, Michael Stimmelmayr, Luiz Clovis Cardoso Vieira, and Jan-Frederick Guth. "Marginal and Internal Fit of Four-unit Zirconia Fixed Dental Prostheses Based on Digital and Conventional Impression Techniques." *Clinical Oral Investigations* (2013).

Colpani, Juliana Tereza, Márcia Borba, and Álvaro Della Bona. "Evaluation of Marginal and Internal Fit of Ceramic Crown Copings." *Dental Materials* 29.2 (2013): 174-80.

Baig, Mirza Rustum, Keson Beng-Choon Tan, and Jack I. Nicholls. "Evaluation of the Marginal Fit of a Zirconia Ceramic Computer-aided Machined (CAM) Crown System." *The Journal of Prosthetic Dentistry* 104.4 (2010): 216-27.

Beuer, Florian, Natalie Korczynski, Antonia Rezac, Michael Naumann, Wolfgang Gernet, and John Sorensen. "Marginal and Internal Fit of Zirconia Based Fixed Dental Prostheses Fabricated with Different Concepts." *Clinical, Cosmetic, and Investigational Dentistry* 2 (2010): 5-11.

Bergenholtz, G., C. F. Cox, W. J. Loesche, and S. A. Syed. "Bacterial Leakage around Dental Restorations: Its Effect on the Dental Pulp." *Journal of Oral Pathology* 11 (1982): 439-50.

Felden, A., G. Schmalz, and KA Hiller. "Retrospective Clinical Study and Survival Analysis on Partial Ceramic Crowns: Results up to Seven Years." *Clinical Oral Investigations* 4 (2000): 199-205.

Toh, C.G., J.C. Setcos, and A.R. Weinstein. "Indirect Dental Laminate Veneers—an Overview." *Journal of Dentistry* 15.3 (1987): 117-24.

Fahmy, Nadia Z. "Influence of Veneering Materials on the Marginal Fit and Fracture Resistance of an Alumina Core System." *Journal of Prosthodontics* 20.1 (2011): 45-51.

Elastomer versus Scanner Impressions

Jamani, K. D., E. Harrington, and H. J. Wilson. "Rigidity of Elastomeric Impression Materials." *Journal of Oral Rehabilitation* 16.3 (1989): 241-48.

Clancy, James M. S., Forrest R. Scandrett, and Ronald L. Ettinger. "Long-term Dimensional Stability of Three Current Elastomers." *Journal of Oral Rehabilitation* 10.4 (1983): 325-33

Endo, Tatsuo, and Werner Finger. "Dimensional Accuracy of a New Polyether Impression Material." *Quintessence International* 37 (2006): 47-51.

Christensen, Gordon J. "The Challenge to Conventional Impressions." *Journal of the American Dental Association* 139.3 (2008): 347-49.

Christensen, Gordon J. "Impressions Are Changing: Deciding on Conventional, Digital or Digital plus In-office Milling." *The Journal of the American Dental Association* 140 (2009): 1301-1304.

Lee, Sang J., and German O. Galluci. "Digital vs. Conventional Implant Impressions: Efficiency Outcomes." *Clinical Oral Implants Research* 1 (2013): 111-115.

Lee, Sang J., Robert X. Macarthur, and German O. Gallucci. "An Evaluation of Student and Clinician Perception of Digital and Conventional Implant Impressions." *The Journal of Prosthetic Dentistry* 110.5 (2013): 420-23.

Yuzbasioglu, Emir, Hanefi Kurt, Rana Turunc, and Halenur Bilir. "Comparison of Digital and Conventional Impression Techniques: Evaluation of Patients' Perception, Treatment Comfort, Effectiveness and Clinical Outcomes." *BMC Oral Health* 14.10 (2014): 1-7.

Conventional Pressing Technique

El-Mowafy, Omar, and Jean-Francois Brochu. "Longevity and Clinical Performance of IPS-Empress Ceramic Restorations--a Literature Review." *Journal of the Canadian Dental Association* 68.4 (2002): 233-37

Dong, JK, H. Luthy, A. Wohlwend, and P. Scharer. "Heat-pressed Ceramics: Technology and Strength." *The International Journal of Prosthodontics* 5.1 (1992)

Holand, Wolfram, Marcel Schweiger, Martin Frank, and Volker Rheinberger. "A Comparison of the Microstructure and Properties of the IPS Empress 2 and the IPS Empress Glass-ceramics." *Journal of Biomedical Materials Research* 53.4 (2000): 297-303.

Lithium Disilicate

Kim, Jee Hwan, Su-Jeong Lee, Jun Sub Park, and Jae Jun Ryu. "Fracture Load of Monolithic CAD/CAM Lithium Disilicate Ceramic Crowns and Veneered Zirconia Crowns as a Posterior Implant Restoration." *Implant Dentistry* 22.1 (2013): 66-70

Tysowsky, G. "The Science behind Lithium Disilicate: A Metal-free Alternative." *Dentistry Today* 28.3 (2009): 112-13.

Ivoclar Vivadent, Inc., Glidewell Dental. “The Future of All-Ceramic Dentistry – Materials Science, Practical Applications, Key to Success.” 2009. http://www.glidewelldental.com/downloads/dentist/services/e.max-lithium-disilicate-scientific.pdf

Altamimi, AM, AP Tripodakis, G. Eliades, and H. Hirayama. "Comparison of Fracture Resistance and Fracture Characterization of Bilayered Zirconia/fluorapatite and Monolithic Lithium Disilicate All Ceramic Crowns." *European Journal of Esthetic Dentistry* 9.1 (2014): 98-110.

Etman, Maged K. "Confocal Examination of Subsurface Cracking in Ceramic Materials." *Journal of Prosthodontics* 18.7 (2009): 550-59.

Lava Chairside Oral Scanner (COS) by 3M ESPE

Rohaly Janos, inventor. Three-channel camera systems with non-collinear apertures. United States Patent 7,372,642; 2006.

Lava Chairside Oral Scanner C.O.S (2009) 3M ESPE Technical Datasheet.

Logozzo S, Franceschini G, Kilpelä A, Caponi M, Governi L, Blois L. “A comparative analysis of intraoral 3d digital scanners for restorative dentistry.” *The Internet Journal of Medical Technology* 2011: 5(1).

Birnbaum, Nathan S., Heidi B. Aaronson, Chris Stevens, and Bob Cohen. "3D Digital Scanners: A High-Tech Approach to More Accurate Dental Impressions." *Inside Dentistry* 5.4 (2009).

Schaefer, Olivia, Mike Decker, Frank Wittstock, Harald Kuepper, and Arndt Guentsch. "Impact of Digital Impression Techniques on the Adaption of Ceramic Partial Crowns in Vitro." *Journal of Dentistry* (2014): In Press.

Meer, Wicher J. Van Der, Frank S. Andriessen, Daniel Wismeijer, and Yijin Ren. "Application of Intra-Oral Dental Scanners in the Digital Workflow of Implantology." Ed. Michael Glogauer. *PLoS ONE* 7.8 (2012): E43312.

Ender, Andreas, and A. Mehl. "Full Arch Scans: Conventional versus Digital Impressions--an In-vitro Study." *International Journal of Computerized Dentistry* 14.1 (2011): 11-21.

Güth, Jan-Frederik, Christine Keul, Michael Stimmelmayr, Florian Beuer, and Daniel Edelhoff. "Accuracy of Digital Models Obtained by Direct and Indirect Data Capturing." *Clinical Oral Investigations* 17.4 (2013): 1201-208.

Computer-Aided Design and Manufacturing (CAD/CAM) Systems

Schaefer, Oliver, Harald Kuepper, Geoffrey A. Thompson, Georg Cachovan, Arthur F. Hefti, and Arndt Guentsch. "Effect of CNC-milling on the Marginal and Internal Fit of Dental Ceramics: A Pilot Study." *Dental Materials* 29.8 (2013): 851-58.

Touchstone, Alex, Tom Nieting, and Norbert Ulmer. 2010 "Digital Transition: The Collaboration between Dentists and Laboratory Technicians on CAD/CAM Restorations." *The Journal of the American Dental Association* 141: 15S-9S.

Beuer, F., J. Schweiger, and D. Edelhoff. "Digital Dentistry: An Overview of Recent Developments for CAD/CAM Generated Restorations." *British Dental Journal* 204.9 (2008): 505-11.

Noort, Richard Van. "The Future of Dental Devices Is Digital." *Dental Materials* 28.1 (2012): 3-12.

Mormann, W. H. "The Evolution of the CEREC System." *Journal of the American Dental Association* 137.1 (2006): 7S-13S.

Guess PC, Zavanelli RA, Silva NR, Bonfante EA, Coelho PG, Thompson VP. “Monolithic CAD/CAM lithium disilicate versus veneered Y-TZP crowns: Comparison of failure modes and reliability after fatigue.” *International Journal of Prosthodontics*. 23(5) 2010: 434-42.

Schmitter M, Mueller D, Rues S. “Chipping behaviour of all-ceramic crowns with zirconia framework and CAD/CAM manufactured veneer.” *Journal of Dentistry*. 2012 154-62.

Digital Workflow and Marginal Integrity

Logozzo, Silvia, Elisabetta M. Zanetti, Giordano Franceschini, Ari Kilpelä, and Anssi Mäkynen. "Recent Advances in Dental Optics – Part I: 3D Intraoral Scanners for Restorative Dentistry." *Optics and Lasers in Engineering* 54 (2014): 203-21

Syrek, Andreas, Gunnar Reich, Dieter Ranftl, Christoph Klein, Barbara Cerny, and Jutta Brodesser. "Clinical Evaluation of All-ceramic Crowns Fabricated from Intraoral Digital Impressions Based on the Principle of Active Wavefront Sampling." *Journal of Dentistry* 38.7 (2010): 553-559.

Scotti, Roberto, Paolo Cardelli, Paolo Baldissara, and Carlo Monaco. "Clinical Fitting of CAD/CAM Zirconia Single Crowns Generated from Digital Intraoral Impressions Based on Active Wavefront Sampling." *Journal of Dentistry* (2011).

Seelbach, Paul, Cora Brueckel, and Bernd Wöstmann. "Accuracy of Digital and Conventional Impression Techniques and Workflow." *Clinical Oral Investigations* 17.7 (2013): 1759-1764.

Anadioti, Evanthia, Steven Aquilino, David Gratton, Julie Halloway, Isabelle Denry, Geb Thomas, and Fang Qian. "3D and 2D Marginal Fit of Pressed and CAD/CAM Lithium Disilicate Crowns Made from Digital and Conventional Impressions." *Journal of Prosthodontics* 23.8 (2014): 610-617.

Anadioti, Evanthia, Steven Aquilino, David Gratton, Julie Halloway, Isabelle Denry, Geb Thomas, and Fang Qian. "Internal Fit of Pressed and Computer-aided Design/computer-aided Manufacturing Ceramic Crowns Made from Digital and Conventional Impressions." *The Journal of Prosthetic Dentistry* 113.4 (2015): 304-09.

Logozzo, Silva, Elisabetta M. Zanett, Giordano Franceschini, Ari Kilpela, and Anssi Makynen. "Recent Advances in Dental Optics – Part I: 3D Intraoral Scanners for Restorative Dentistry." *Optics and Lasers in Engineering* 54 (2014): 203-21.

Lin, Wei-Shao, Amirali Zandinejad, Michael Metz, Brandon Harris, and Dean Morton. “Predictable Restorative Work Flow for Computer-Aided Design/Computer-Aided Manufacture– Fabricated Ceramic Veneers Utilizing a Virtual Smile Design Principle.” *Operative Dentistry* 40.3 (2015).

Zandinejad, Amirali, W. Lin, M. Atarodi, M. Metz, and D. Morton. "Digital Workflow for Virtually Designing and Milling Ceramic Lithium Disilicate Veneers: A Clinical Report." *Operative Dentistry* 40.3 (2015).

Lee, Sang J., Robert X. Macarthur, and German O. Gallucci. "An Evaluation of Student and Clinician Perception of Digital and Conventional Implant Impressions." *The Journal of Prosthetic Dentistry* 110.5 (2013): 420-23.

DISCUSSION

Tsitrou, Effrosyni A., Simon E. Northeast, and Richard Van Noort. "Brittleness Index of Machinable Dental Materials and Its Relation to the Marginal Chipping Factor." *Journal of Dentistry* 35.12 (2007): 897-902.

Giannetopoulos, Sotiris, Richard Van Noort, and Effrosyni Tsitrou. "Evaluation of the Marginal Integrity of Ceramic Copings with Different Marginal Angles Using Two Different CAD/CAM Systems." *Journal of Dentistry* 38.12 (2010): 980-86.

Balakrishnama S, Wenzel K, Bergeron J, Ruest C, Reusch B, Kugel G. “Dimensional repeatability from the Lava COS 3D intra-oral scanning system.” *Journal of Dental Research* 88(A) (2009)

Zandinejad, Amirali, W. Lin, M. Atarodi, M. Metz, and D. Morton. "Digital Workflow for Virtually Designing and Milling Ceramic Lithium Disilicate Veneers: A Clinical Report." *Operative Dentistry* 40.3 (2015).

Zandinejad, Amirali, Michael Metz, Paul Stevens, Wei-Shaq Lin, and Dean Morton. "Virtually Designed and CAD/CAM-fabricated Lithium Disilicate Prostheses for an Esthetic Maxillary Rehabilitation: A Senior Dental Student Clinical Report." *The Journal of Prosthetic Dentistry* 113.4 (2015): 282-88.

Abdel-Azim, Tamer, Amirali Zandinejad, Michael Metz, and Dean Morton. “Maxillary and Mandibular Rehabilitation in the Esthetic Zone Using a Digital Impression Technique and CAD/CAM-fabricated Prostheses: A Multidisciplinary Clinical Report.” *Operative Dentistry* 40.3 (2015).

Baig, Mirza Rustum, Keson Beng-Choon Tan, and Jack I. Nicholls. "Evaluation of the Marginal Fit of a Zirconia Ceramic Computer-aided Machined (CAM) Crown System." *The Journal of Prosthetic Dentistry* 104.4 (2010): 216-27.

Shahrbaf, Shirin, Richard Van Noort, Behnam Mirzakouchaki, Elaheh Ghassemieh, and Nicolas Martin. "Fracture Strength of Machined Ceramic Crowns as a Function of Tooth Preparation Design and the Elastic Modulus of the Cement." *Dental Materials* 30.2 (2014): 234-41.

Brawek, Petya, Stefan Wolfart, Lutz Endres, Armin Kirsten, and Sven Reich. “The clinical accuracy of single crowns exclusively fabricated by digital workflow – the comparison of two systems.” *Clinical Oral Investigations* 17.2 (2013): 2119-212.

Anadioti, Evanthia, Steven Aquilino, David Gratton, Julie Halloway, Isabelle Denry, Geb Thomas, and Fang Qian. "3D and 2D Marginal Fit of Pressed and CAD/CAM Lithium Disilicate Crowns Made from Digital and Conventional Impressions." *Journal of Prosthodontics* 23.8 (2014): 610-617.

Anadioti, Evanthia, Steven Aquilino, David Gratton, Julie Halloway, Isabelle Denry, Geb Thomas, and Fang Qian. "Internal Fit of Pressed and Computer-aided Design/computer-aided Manufacturing Ceramic Crowns Made from Digital and Conventional Impressions." *The Journal of Prosthetic Dentistry* 113.4 (2015): 304-09.

APPENDIX A

TABULATED RAW DATA

Group	Sample	Position	Smallest	Best Fit	Largest	Mean	SD
G1	S1-P1	P1	113.98	146.24	184.95	148.39	35.53
G1	S1-P2	P2	113.98	135.48	163.44	137.63	24.8
G1	S1-P3	P3	103.23	176.34	176.34	151.97	42.22
G1	S1-B1	B1	27.96	49.46	53.76	43.73	13.83
G1	S1-B2	B2	51.61	126.88	163.44	113.98	57.02
G1	S1-B3	B3	27.96	32.26	73.12	44.44	24.93
G1	S1-M1	M1	19.36	30.11	32.26	27.24	6.91
G1	S1-M2	M2	32.26	58.07	62.37	50.9	16.28
G1	S1-M3	M3	23.66	32.26	36.56	30.82	6.57
G1	S1-D1	D1	27.96	40.86	70.97	46.5	22.07
G1	S1-D2	D2	32.26	96.77	113.98	81	43.08
G1	S1-D3	D3	17.2	23.66	23.66	21.51	3.73
G1	S2-P1	P1	300.43	311.16	347.64	319.74	24.75
G1	S2-P2	P2	308.17	320.83	339.83	322.94	15.94
G1	S2-P3	P3	303.95	314.5	341.94	320.13	19.61
G1	S2-B1	B1	211.07	238.51	280.73	243.44	35.08
G1	S2-B2	B2	179.41	192.08	230.07	200.52	26.36
G1	S2-M1	M1	19.31	38.63	64.38	40.77	22.61
G1	S2-M2	M2	364.22	381.47	396.55	380.75	16.18
G1	S2-M3	M3	178.11	182.4	184.55	181.69	3.38
G1	S2-D1	D1	189.66	211.21	226.29	209.05	18.41
G1	S2-D2	D2	298.28	330.37	332.62	320.46	19.23
G1	S2-D3	D3	64.38	120.17	128.76	104.44	34.96
G1	S3-P1	P1	166.75	170.97	187.86	175.19	11.17
G1	S3-P2	P2	160.42	175.19	194.19	176.6	16.93
G1	S3-P3	P3	139.49	186.7	199.57	175.25	32.64
G1	S3-B1	B1	115.88	124.46	128.76	123.03	5.56
G1	S3-B2	B2	98.71	148.07	90.09	145.92	46.18
G1	S3-B3	B3	72.96	109.44	137.34	106.58	32.28
G1	S3-M1	M1	19.31	55.79	126.61	67.24	54.56
G1	S3-M2	M2	62.5	112.07	127.16	100.58	33.83
G1	S3-M3	M3	40.77	60.09	81.55	60.8	20.4
G1	S3-D1	D1	167.38	170.23	175.96	170.24	4.96
G1	S3-D2	D2	118.03	182.8	195.28	165.24	41.39

G1	S3-D3	D3	85.84	118.03	139.49	114.45	27
G1	S4-P1	P1	139.49	175.97	184.55	166.67	23.93
G1	S4-P2	P2	139.49	141.63	171.67	150.93	18
G1	S4-P3	P3	171.67	178.11	199.57	183.12	14.61
G1	S4-B1	B1	83.69	105.15	137.34	108.73	27
G1	S4-B2	B2	92.28	156.65	169.53	139.49	41.39
G1	S4-B3	B3	77.25	113.73	115.88	102.29	21.71
G1	S4-M1	M1	25.75	51.5	90.13	55.79	32.4
G1	S4-M2	M2	55.79	124.46	137.34	105.87	43.84
G1	S4-M3	M3	32.18	36.48	64.38	44.35	17.48
G1	S4-D1	D1	98.71	107.3	111.59	105.87	6.56
G1	S4-D2	D2	87.98	90.13	90.13	89.41	1.24
G1	S4-D3	D3	79.4	100.86	122.32	100.86	21.46
G1	S5-P1	P1	92.28	103	130.9	108.73	19.94
G1	S5-P2	P2	94.42	107.3	124.46	108.73	15.07
G1	S5-P3	P3	92.28	115.88	122.32	110.16	15.82
G1	S5-B1	B1	55.79	113.73	120.17	96.57	35.36
G1	S5-B2	B2	81.55	135.19	141.63	119.46	32.99
G1	S5-B3	B3	30.17	71.12	94.83	65.37	32.71
G1	S5-M1	M1	25.75	45.06	55.79	42.2	15.22
G1	S5-M2	M2	34.34	66.52	94.42	65.09	30.07
G1	S5-M3	M3	19.31	30.04	75.11	41.49	29.61
G1	S5-D1	D1	45.06	51.5	66.52	54.43	11.01
G1	S5-D2	D2	55.79	96.57	135.19	95.85	39.7
G1	S5-D3	D3	32.19	62.23	75.11	56.51	22.02
G1	S6-P1	P1	233.41	237.69	254.82	241.97	11.33
G1	S6-P2	P2	224.84	235.55	248.39	236.26	11.79
G1	S6-P3	P3	237.69	259.1	269.81	255.53	16.36
G1	S6-B1	B1	113.49	124.2	156.32	131.34	22.29
G1	S6-B2	B2	94.22	137.05	169.17	133.48	37.6
G1	S6-B3	B3	81.37	137.05	177.73	132.05	48.37
G1	S6-M1	M1	126.34	158.46	167.02	150.61	21.45
G1	S6-M2	M2	139.19	171.31	214.13	174.88	37.6
G1	S6-M3	M3	203.43	220.56	254.82	226.27	26.17
G1	S6-D1	D1	216.27	235.55	248.39	233.4	16.17
G1	S6-D2	D2	231.26	321.2	353.32	301.93	63.27
G1	S6-D3	D3	139.19	149.89	201.29	163.46	33.2
G1	S7-P1	P1	158.46	184.15	216.27	186.3	28.97
G1	S7-P2	P2	169.17	184.15	192.72	182.01	11.92

G1	S7-P3	P3	171.31	209.85	230.69	206.28	33.33
G1	S7-B1	B1	134.9	134.9	143.47	137.76	4.95
G1	S7-B2	B2	102.78	115.63	175.59	131.34	38.86
G1	S7-B3	B3	98.5	130.62	154.18	127.77	27.95
G1	S7-M1	M1	27.84	83.51	119.91	77.09	46.37
G1	S7-M2	M2	17.13	36.4	44.97	32.83	14.26
G1	S7-M3	M3	81.37	100.64	109.21	97.07	14.26
G1	S7-D1	D1	21.41	27.84	29.98	26.41	4.46
G1	S7-D2	D2	25.7	130.62	241.97	132.76	108.15
G1	S7-D3	D3	25.7	34.26	68.52	42.83	22.66
G1	S8-P1	P1	263.53	329.76	329.76	308.35	37.09
G1	S8-P2	P2	331.91	338.33	349.04	339.76	8.65
G1	S8-P3	P3	286.94	291.22	316.92	298.36	16.21
G1	S8-B1	B1	132.76	134.9	152.03	139.9	10.56
G1	S8-B2	B2	141.33	154.18	199.14	164.88	30.36
G1	S8-B3	B3	173.45	175.59	188.44	179.16	8.11
G1	S8-M1	M1	128.48	156.32	209.85	164.88	41.36
G1	S8-M2	M2	219.83	336.21	415.95	323.99	98.63
G1	S8-M3	M3	209.89	226.95	263.28	233.45	27.34
G1	S8-D1	D1	60.09	109.44	156.65	108.73	48.29
G1	S8-D2	D2	214.59	300.43	326.18	280.4	58.43
G1	S8-D3	D3	51.61	75.27	122.58	83.15	36.14
G1	S9-P1	P1	152.69	178.5	189.25	173.48	18.79
G1	S9-P2	P2	165.59	187.1	212.9	188.53	23.69
G1	S9-P3	P3	150.54	172.04	184.95	169.18	17.83
G1	S9-B1	B1	58.07	90.32	129.03	92.47	35.53
G1	S9-B2	B2	62.37	88.17	133.33	94.62	35.92
G1	S9-B3	B3	45.16	66.67	70.97	60.93	13.83
G1	S9-M1	M1	55.91	86.02	148.39	96.77	47.17
G1	S9-M2	M2	79.57	116.13	150.54	115.14	35.49
G1	S9-M3	M3	23.66	25.81	38.71	29.39	8.14
G1	S9-D1	D1	45.16	49.46	70.97	55.2	13.83
G1	S9-D2	D2	83.87	107.53	161.29	117.56	39.67
G1	S9-D3	D3	189.25	191.4	232.26	204.3	24.24
G1	S10-P1	P1	283.87	311.83	333.33	309.67	24.8
G1	S10-P2	P2	294.62	305.38	305.38	301.79	6.21
G1	S10-P3	P3	298.93	333.33	339.79	324.01	21.97
G1	S10-B1	B1	182.8	210.75	230.11	207.89	23.79
G1	S10-B2	B2	184.95	251.61	290.32	242.29	53.3

G1	S10-B3	B3	141.94	200	163.44	168.46	29.36
G1	S10-M1	M1	17.2	51.61	92.47	53.76	37.68
G1	S10-M2	M2	178.5	232.26	279.57	230.11	50.57
G1	S10-M3	M3	154.84	225.81	232.26	204.3	42.96
G1	S10-D1	D1	150.54	197.85	210.57	186.38	31.7
G1	S10-D2	D2	156.99	230.11	232.26	206.45	42.85
G1	S10-D3	D3	12.9	64.52	70.97	49.46	31.83
G2	S1-P1	P1	38.67	47.21	60.08	48.64	10.8
G2	S1-P2	P2	17.17	25.75	42.92	28.61	13.11
G2	S1-P3	P3	32.19	34.34	49.36	38.62	13.11
G2	S1-B1	B1	30.04	60.09	96.57	62.23	33.31
G2	S1-B2	B2	23.22	52.77	90.76	55.58	33.86
G2	S1-B3	B3	64.37	87.98	107.3	86.55	21.49
G2	S1-M1	M1	109.44	118.74	167.38	118.74	44.73
G2	S1-M2	M2	62.23	109.22	150.12	107.3	44.03
G2	S1-M3	M3	199.57	251.78	319.74	251.79	61.62
G2	S1-D1	D1	90.13	143.77	298.28	177.4	108.07
G2	S1-D2	D2	79.4	130.9	242.48	150.93	83.37
G2	S1-D3	D3	135.19	180.27	266.09	193.19	66.5
G2	S2-P1	P1	10.73	27.9	62.23	33.62	26.22
G2	S2-P2	P2	32.19	42.92	60.86	45.06	14.07
G2	S2-P3	P3	30.04	45.06	62.23	45.78	16.11
G2	S2-B1	B1	55.79	70.82	122.32	82.97	34.89
G2	S2-B2	B2	70.81	111.61	165.25	90.61	47.36
G2	S2-B3	B3	55.79	81.54	115.88	84.41	30.14
G2	S2-M1	M1	45.06	130.91	156.65	110.87	58.42
G2	S2-M2	M2	141.63	197.42	300.43	141.63	80.56
G2	S2-M3	M3	77.25	107.29	167.38	117.31	45.89
G2	S2-D1	D1	171.67	214.59	281.11	222.46	55.14
G2	S2-D2	D2	85.84	156.65	186.69	143.06	51.78
G2	S2-D3	D3	201.72	266.09	300.43	256.08	50.12
G2	S3-P1	P1	8.62	19.4	28.02	18.68	9.72
G2	S3-P2	P2	17.16	27.9	32.19	25.75	7.73
G2	S3-P3	P3	4.3	12.93	28.02	15.09	12
G2	S3-B1	B1	38.79	49.57	56.03	48.13	8.71
G2	S3-B2	B2	43.1	101.29	140.09	94.83	48.81
G2	S3-B3	B3	19.4	25.86	28.07	24.43	4.49
G2	S3-M1	M1	99.14	116.39	122.85	112.79	12.26
G2	S3-M2	M2	109.44	113.73	171.67	131.62	34.76

G2	S3-M3	M3	116.38	140.09	140.09	145.12	31.55
G2	S3-D1	D1	130.9	190.99	298.28	206.72	84.79
G2	S3-D2	D2	21.55	36.64	101.29	53.16	42.36
G2	S3-D3	D3	214.59	296.13	324.03	278.26	56.87
G2	S4-P1	P1	25.86	45.26	84.05	51.72	29.63
G2	S4-P2	P2	32.33	38.79	49.57	40.23	8.71
G2	S4-P3	P3	25.86	49.57	56.03	43.82	15.89
G2	S4-B1	B1	36.64	45.26	60.35	47.41	12
G2	S4-B2	B2	21.55	49.57	75.43	48.85	26.95
G2	S4-B3	B3	30.17	38.79	60.35	43.1	15.54
G2	S4-M1	M1	32.33	34.48	45.26	37.36	6.93
G2	S4-M2	M2	12.93	28.02	32.33	24.43	10.19
G2	S4-M3	M3	66.81	68.97	84.05	73.28	9.39
G2	S4-D1	D1	153.02	191.81	196.12	180.32	23.74
G2	S4-D2	D2	206.9	230.6	237.07	224.86	15.89
G2	S4-D3	D3	51.72	114.22	165.95	110.63	57.2
G2	S5-P1	P1	17.24	25.86	45.26	29.45	14.35
G2	S5-P2	P2	23.71	45.26	56.03	41.67	16.46
G2	S5-P3	P3	19.4	23.71	25.86	22.99	3.29
G2	S5-B1	B1	28.02	36.64	79.74	48.13	27.71
G2	S5-B2	B2	68.97	114.22	153.02	112.07	42.07
G2	S5-B3	B3	25.86	25.86	34.48	28.74	4.98
G2	S5-M1	M1	17.24	25.86	32.33	25.14	7.57
G2	S5-M2	M2	19.4	23.71	36.64	26.58	8.97
G2	S5-M3	M3	32.33	51.72	88.36	57.47	28.46
G2	S5-D1	D1	221.98	262.93	308.19	264.37	43.12
G2	S5-D2	D2	256.46	334.05	400.86	330.46	72.27
G2	S5-D3	D3	198.28	226.29	245.69	223.42	23.84
G2	S6-P1	P1	25.86	28.02	32.33	28.74	3.29
G2	S6-P2	P2	10.78	17.24	19.4	15.81	4.47
G2	S6-P3	P3	19.4	21.55	60.35	33.76	23.05
G2	S6-B1	B1	30.17	36.67	49.57	38.79	9.88
G2	S6-B2	B2	64.66	81.9	159.48	102.01	50.51
G2	S6-B3	B3	30.17	32.33	45.26	35.92	8.16
G2	S6-M1	M1	17.24	28.02	30.17	25.14	6.93
G2	S6-M2	M2	49.57	115.38	150.86	105.6	51.5
G2	S6-M3	M3	21.55	51.72	58.19	43.82	19.56
G2	S6-D1	D1	278.02	280.17	284.48	280.89	3.29
G2	S6-D2	D2	286.64	314.55	321.12	307.47	18.33

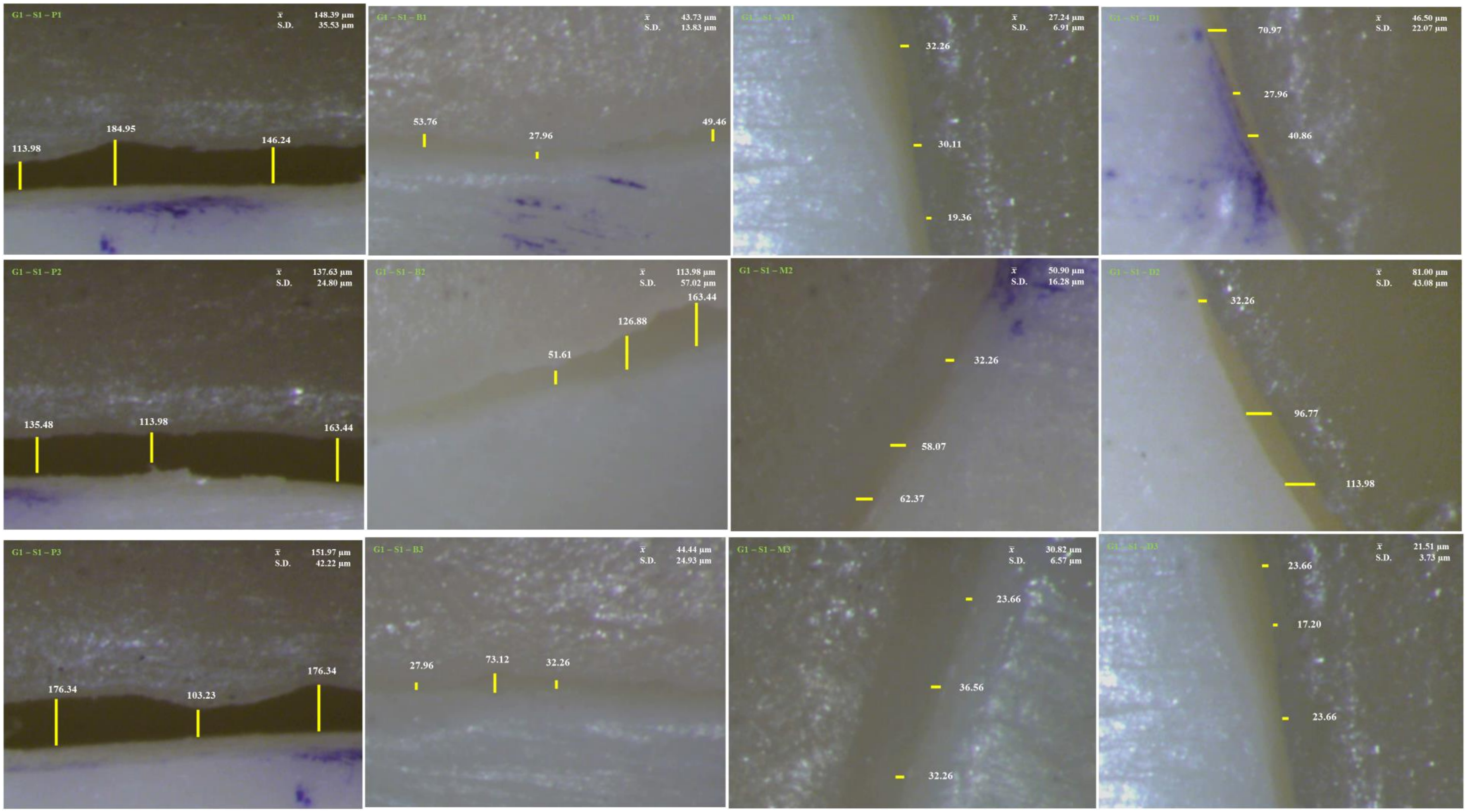
G2	S6-D3	D3	99.14	109.91	114.22	107.76	7.77
G2	S7-P1	P1	8.62	28.12	32.33	22.99	12.63
G2	S7-P2	P2	15.09	38.79	45.26	33.05	15.89
G2	S7-B1	B1	15.09	43.1	51.72	36.64	19.16
G2	S7-B2	B2	21.55	49.57	60.35	43.82	20.03
G2	S7-B3	B3	19.4	23.71	30.17	24.43	5.42
G2	S7-M1	M1	19.4	30.17	45.26	31.61	12.99
G2	S7-M2	M2	6.47	17.24	25.86	16.52	9.72
G2	S7-M3	M3	183.19	219.83	241.38	214.8	29.42
G2	S7-D1	D1	105.6	174.57	215.52	165.23	55.55
G2	S7-D2	D2	36.64	45.26	92.67	58.19	30.17
G2	S7-D3	D3	237.07	243.53	299.57	260.06	34.37
G2	S8-P1	P1	30.04	45.06	60.09	45.06	15.02
G2	S8-P2	P2	51.5	60.09	68.67	60.09	8.59
G2	S8-P3	P3	23.6	40.77	70.86	45.06	23.9
G2	S8-B1	B1	19.4	34.48	51.72	35.2	16.18
G2	S8-B2	B2	17.24	28.02	40.95	28.74	11.87
G2	S8-B3	B3	38.63	66.63	98.71	67.95	30.07
G2	S8-M1	M1	32.19	64.38	109.44	68.67	38.67
G2	S8-M2	M2	87.98	143.78	182.43	138.05	47.47
G2	S8-M3	M3	96.57	124.46	182.4	134.47	43.79
G2	S8-D1	D1	12.87	55.79	145.92	71.53	67.91
G2	S8-D2	D2	21.46	90.13	152.36	87.98	65.48
G2	S8-D3	D3	83.69	163.09	225.32	157.37	70.99
G2	S9-P1	P1	332.62	358.37	405.58	365.52	37
G2	S9-P2	P2	422.75	467.81	502.15	464.23	39.82
G2	S9-P3	P3	278.01	309.58	349.78	312.59	35.54
G2	S9-B1	B1	21.46	27.89	49.36	32.9	14.61
G2	S9-B2	B2	17.17	57.94	169.54	81.55	78.88
G2	S9-B3	B3	10.73	27.89	47.21	28.61	18.25
G2	S9-M1	M1	364.81	399.14	439.91	401.28	37.6
G2	S9-M2	M2	377.16	396.55	454.74	409.48	40.38
G2	S9-M3	M3	263.95	300.43	444.21	336.19	95.3
G2	S9-D1	D1	10.73	42.91	105.15	52.93	48
G2	S9-D2	D2	23.6	40.77	103	55.79	41.78
G2	S9-D3	D3	17.24	23.71	25.86	22.27	4.49
G2	S10-P1	P1	19.31	30.04	45.06	31.47	12.93
G2	S10-P2	P2	15.02	25.75	55.79	32.19	21.13
G2	S10-P3	P3	27.89	51.5	66.52	48.64	19.47

G2	S10-B1	B1	32.18	66.52	87.98	62.23	28.14
G2	S10-B2	B2	40.77	60.09	115.88	72.24	39
G2	S10-B3	B3	49.35	57.94	79.4	62.23	15.47
G2	S10-M1	M1	19.31	25.75	34.35	26.47	7.54
G2	S10-M2	M2	36.48	47.21	60.09	47.92	11.82
G2	S10-M3	M3	23.61	30.04	38.63	30.76	7.54
G2	S10-D1	D1	55.79	85.83	109.44	83.84	26.89
G2	S10-D2	D2	92.28	130.92	208.17	143.79	59
G2	S10-D3	D3	150.22	167.38	212.45	176.68	32.14

APPENDIX B

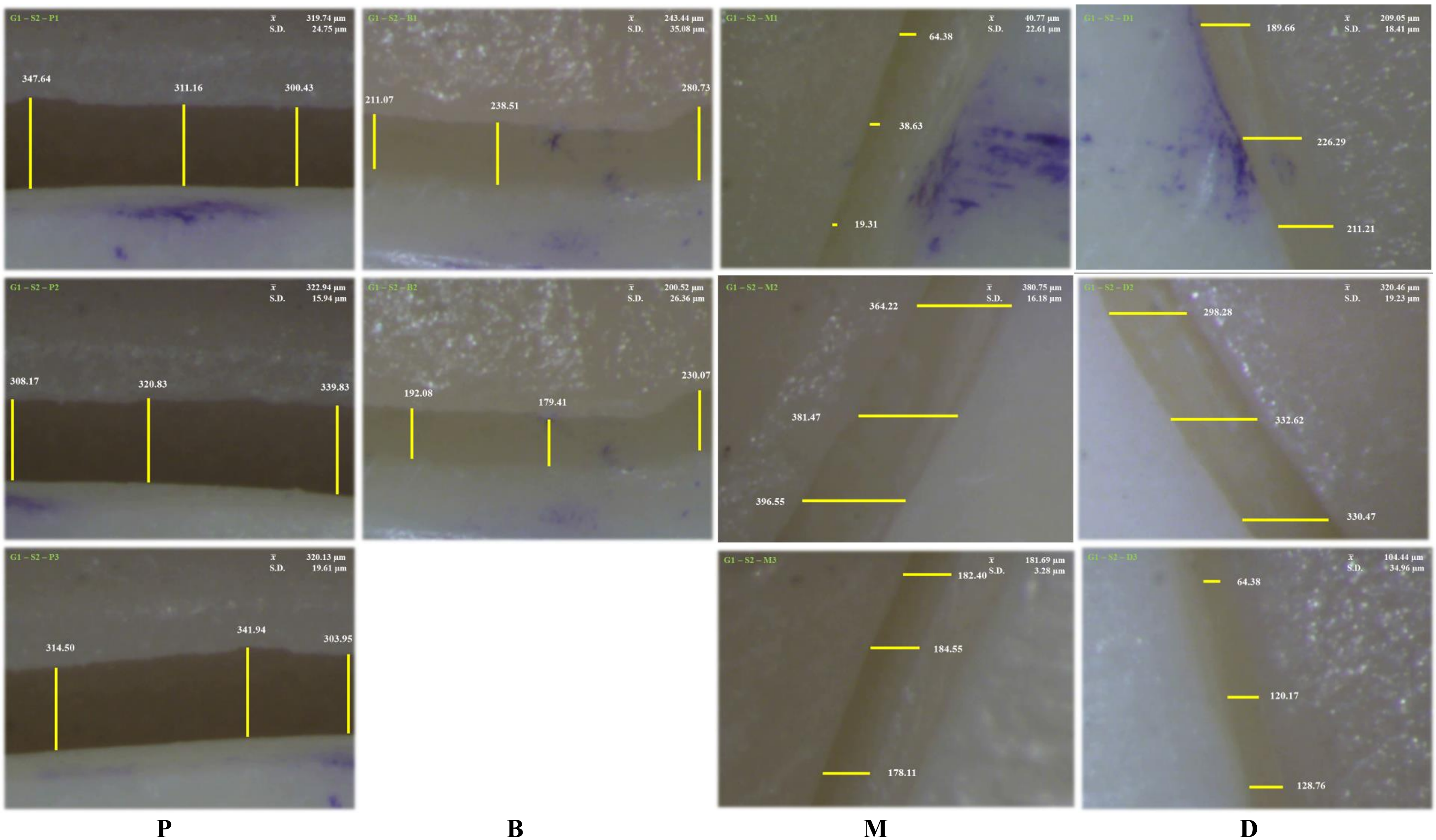
STEREOMICROPE IMAGES – DIGITAL

<u>GROUP 1: SAMPLE 1</u>

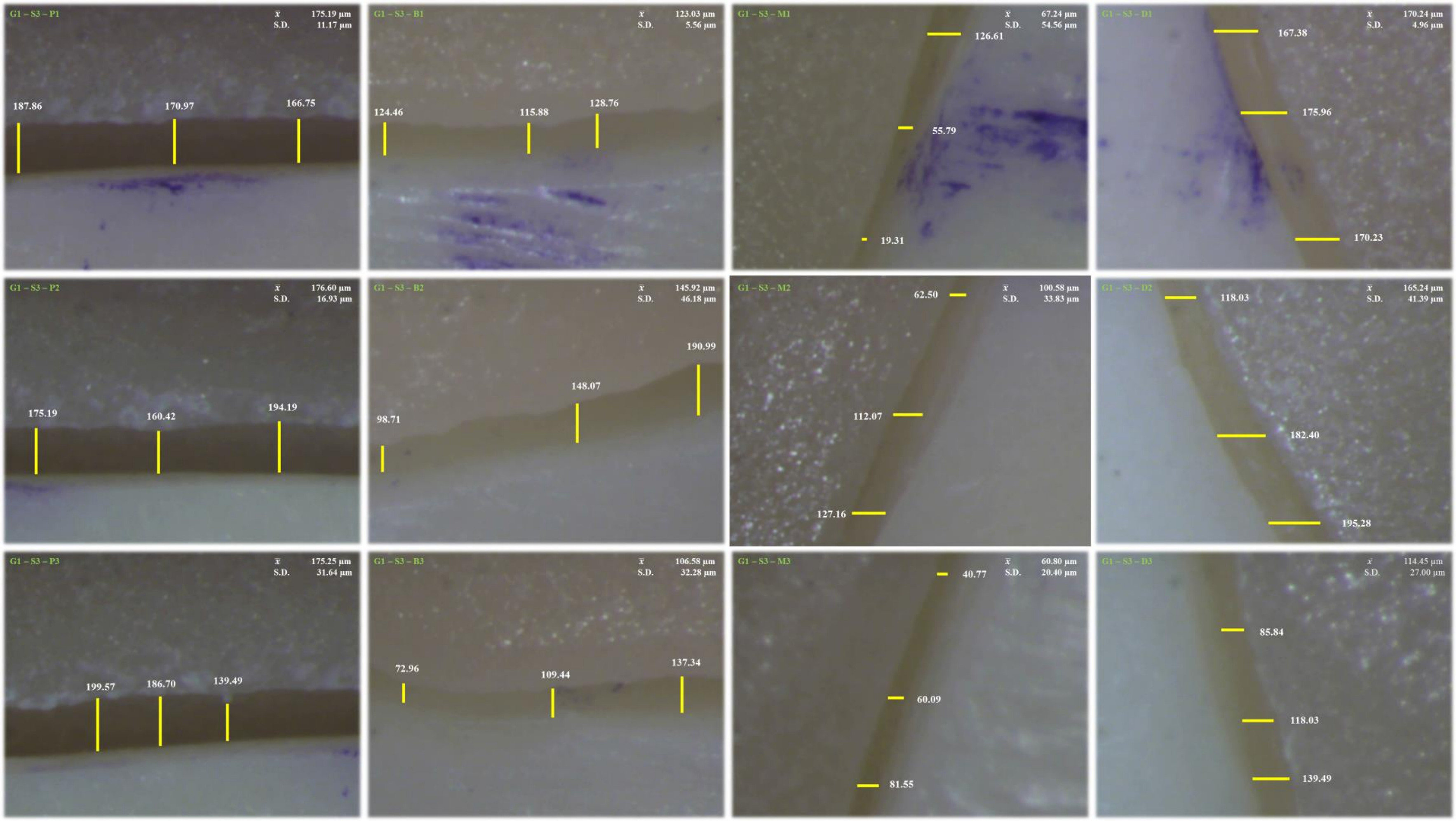


P **B** **M** **D**

GROUP 1: SAMPLE 2

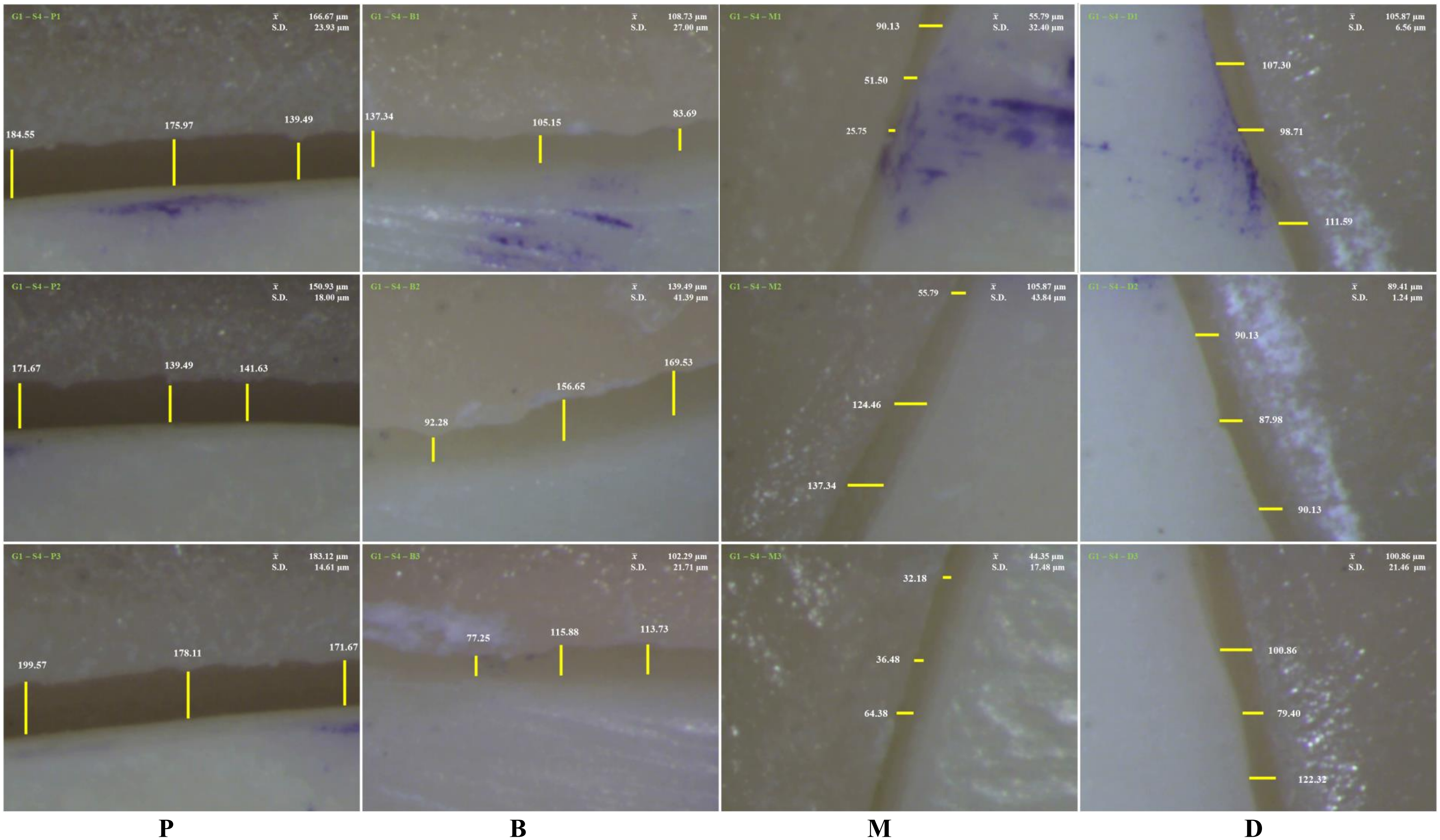


GROUP 1: SAMPLE 3

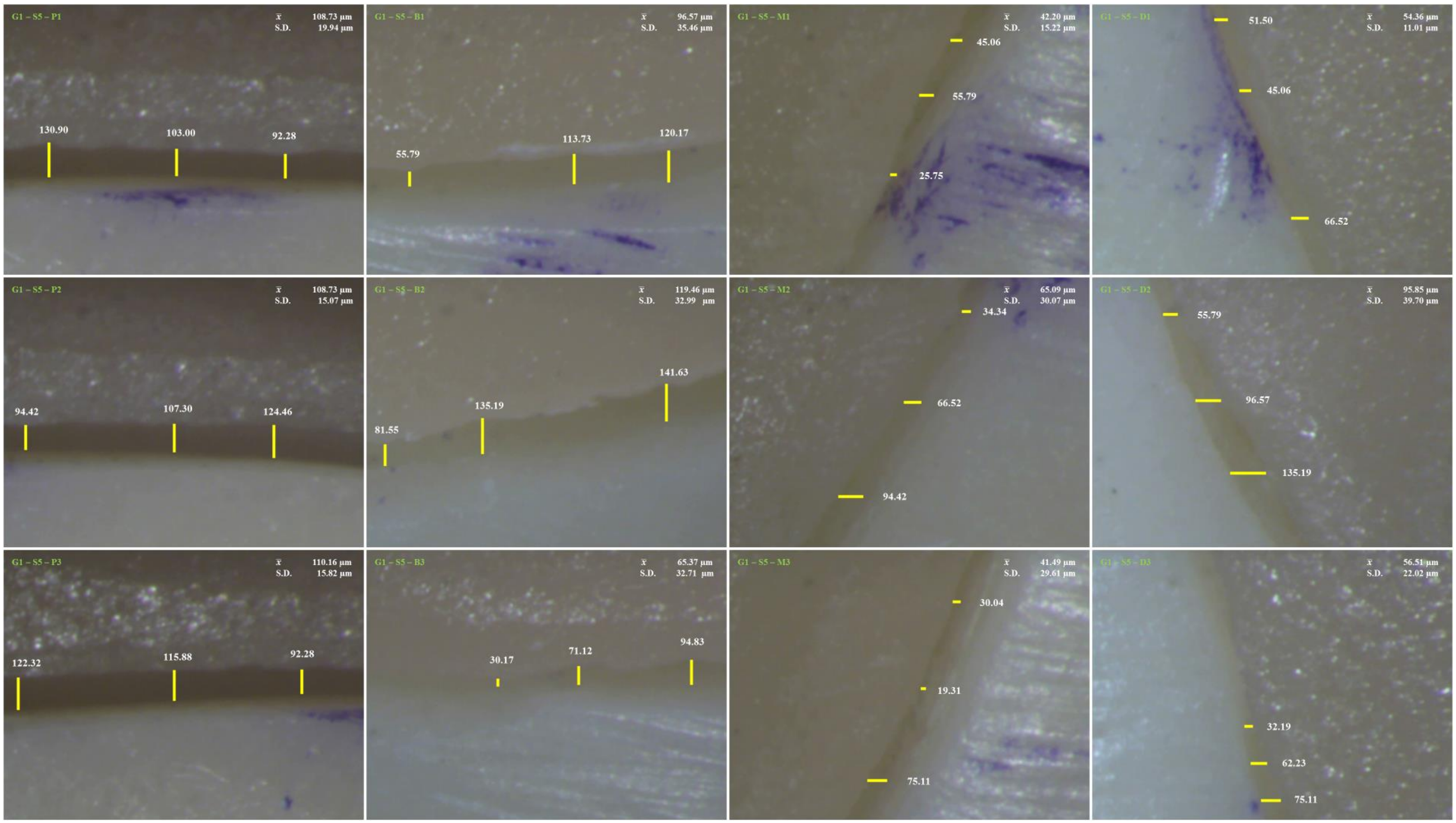


P **B** **M** **D**

GROUP 1: SAMPLE 4

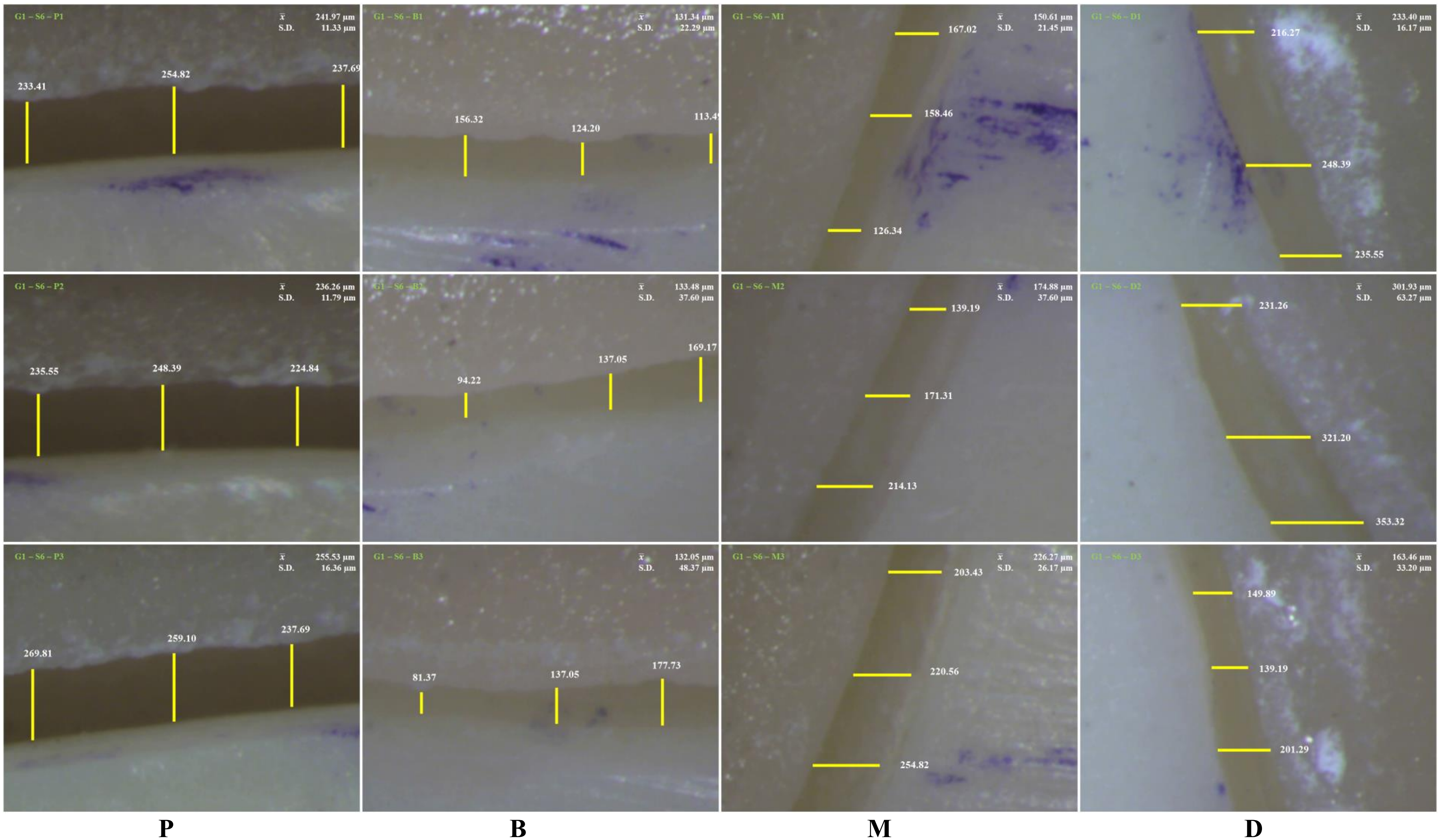


GROUP 1: SAMPLE 5

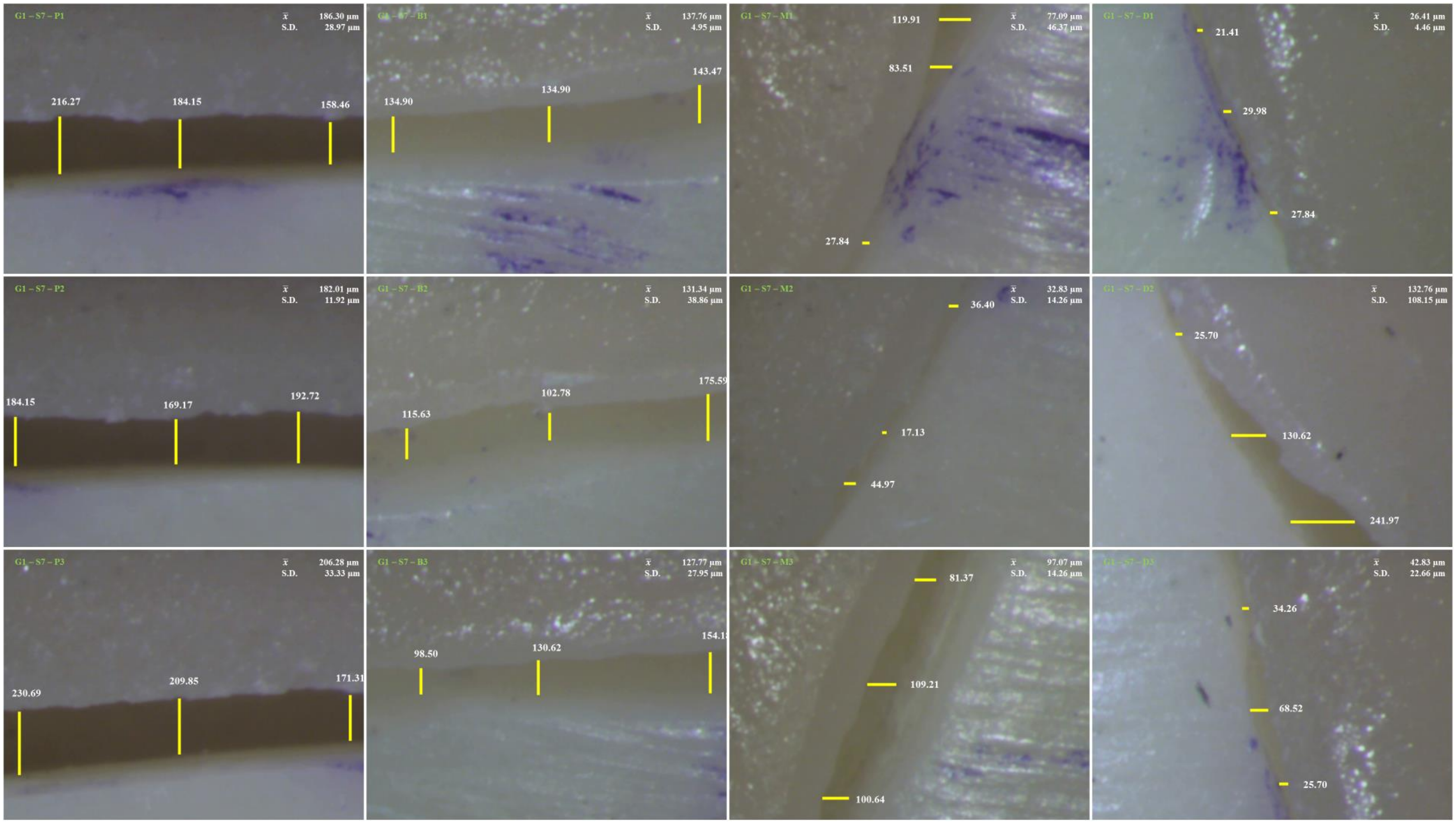


P **B** **M** **D**

GROUP 1: SAMPLE 6

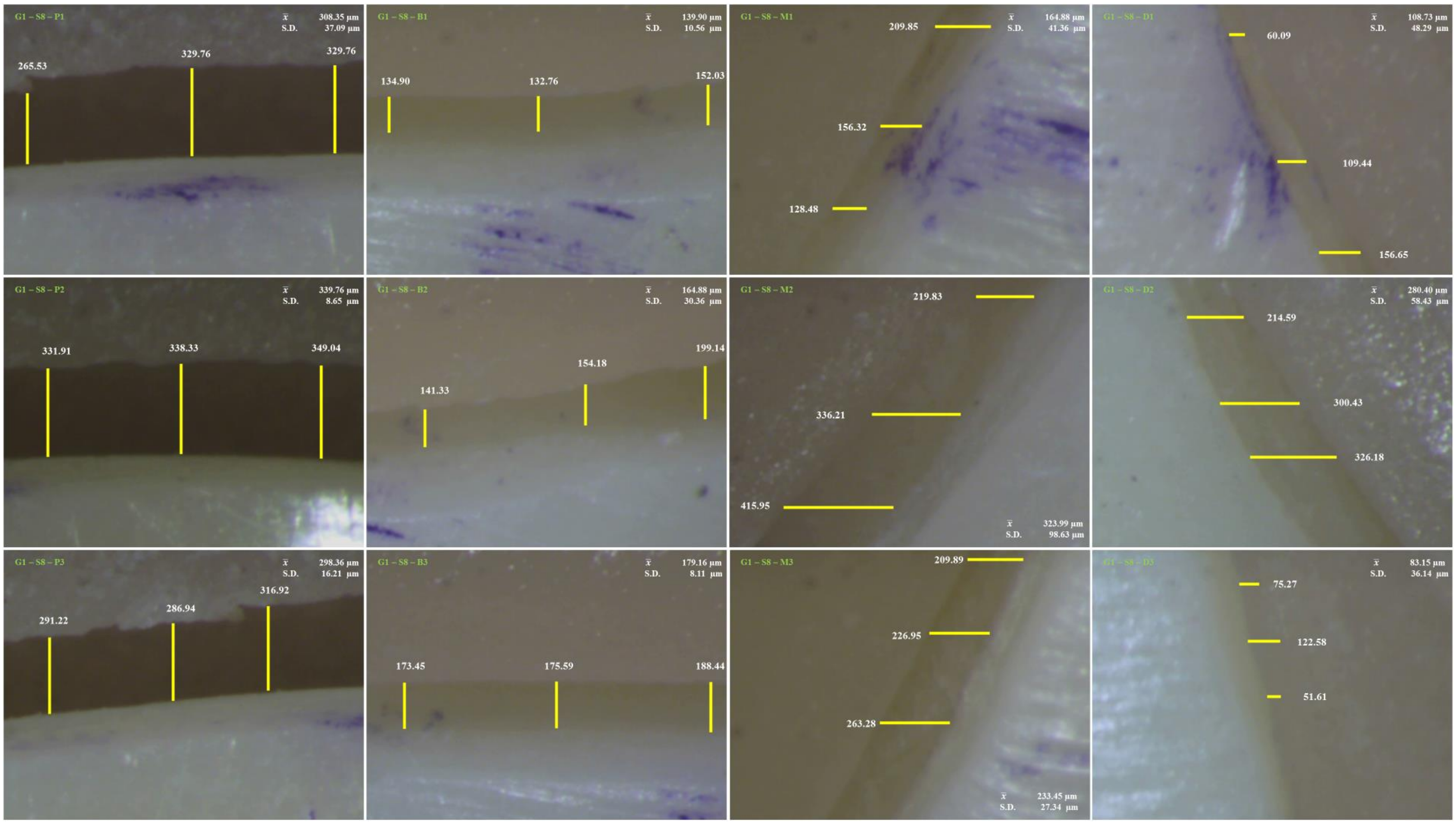


GROUP 1: SAMPLE 7



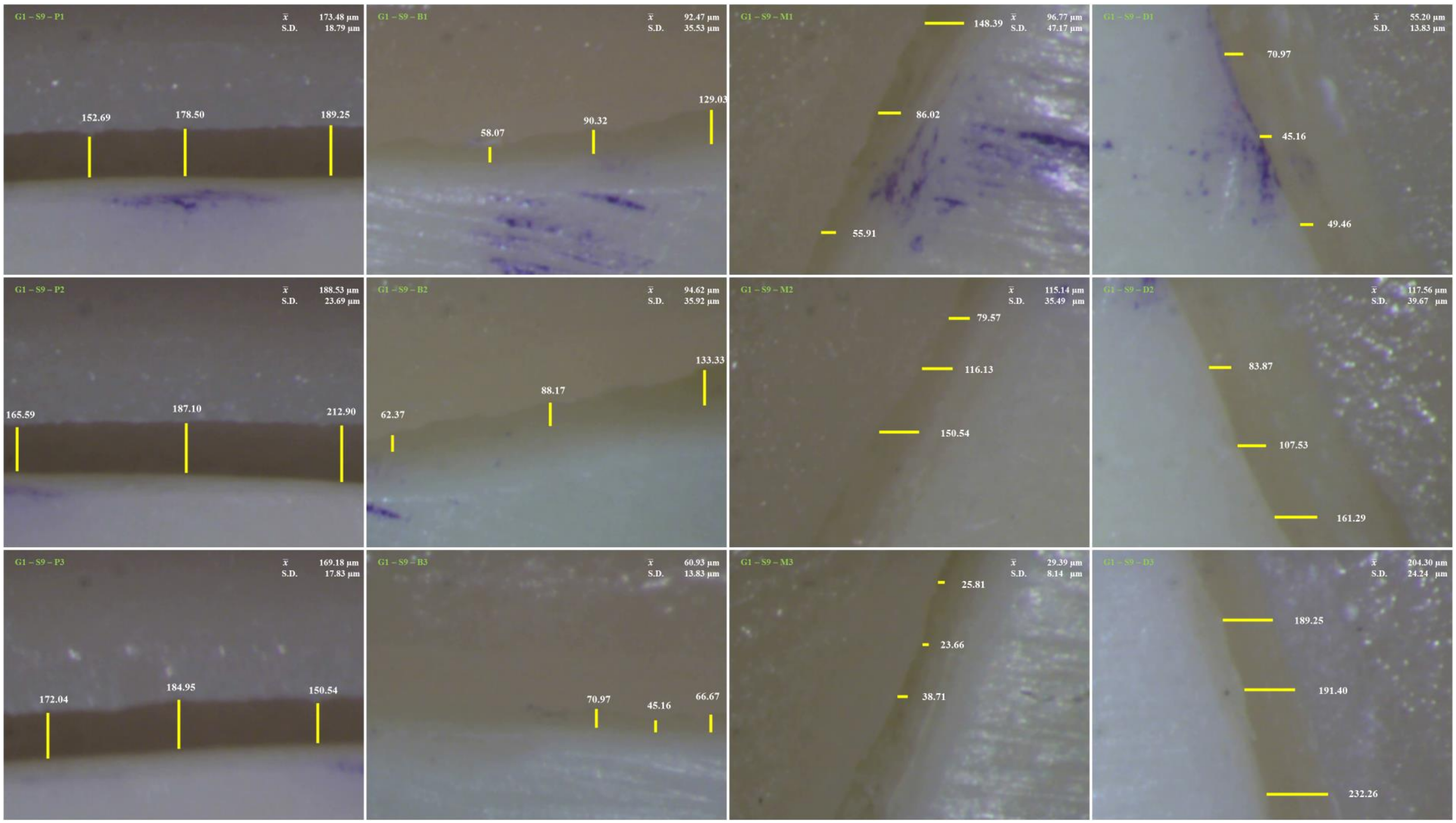
P **B** **M** **D**

<u>GROUP 1: SAMPLE 8</u>



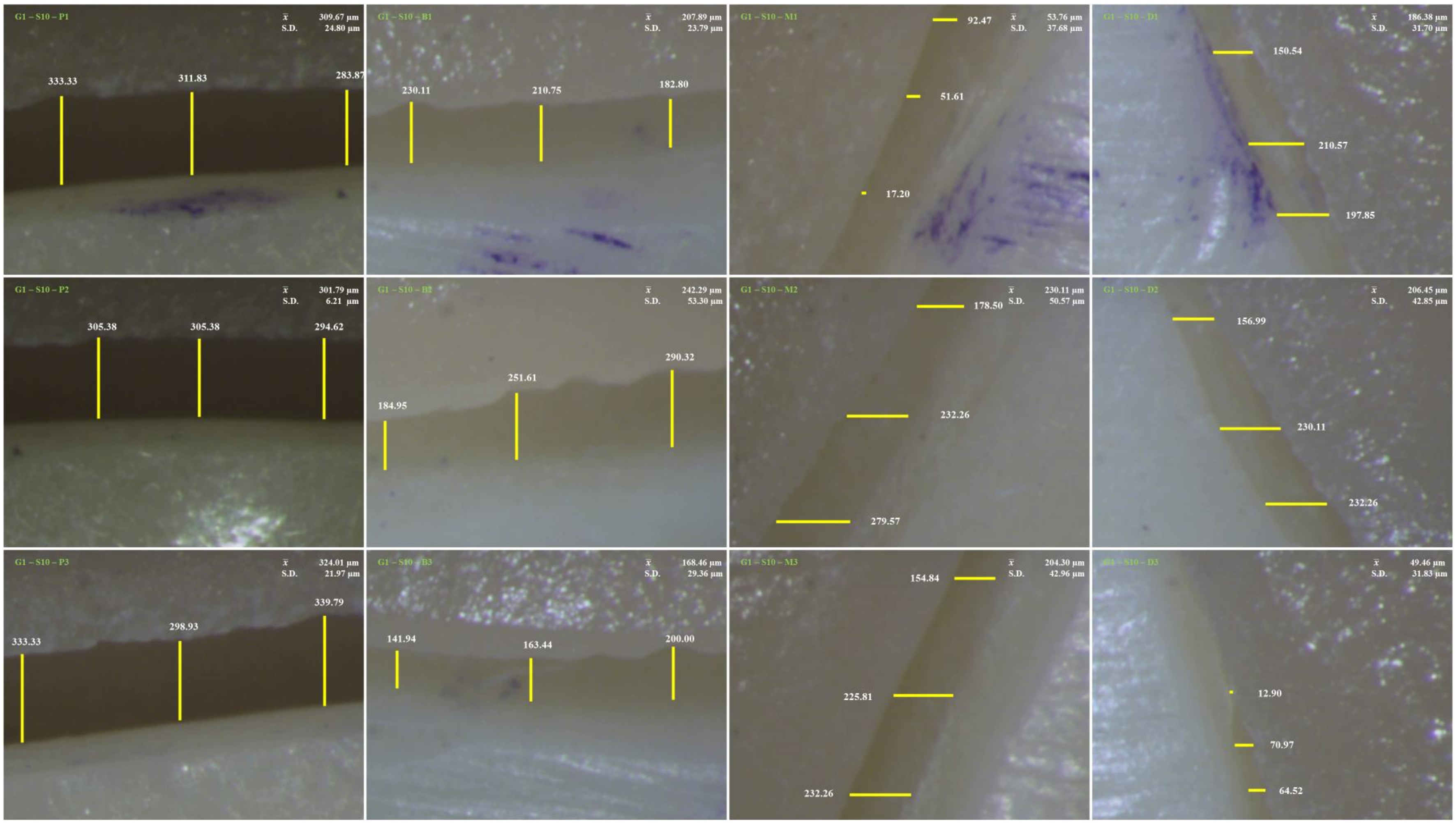
P **B** **M** **D**

GROUP 1: SAMPLE 9



P **B** **M** **D**

GROUP 1: SAMPLE 10

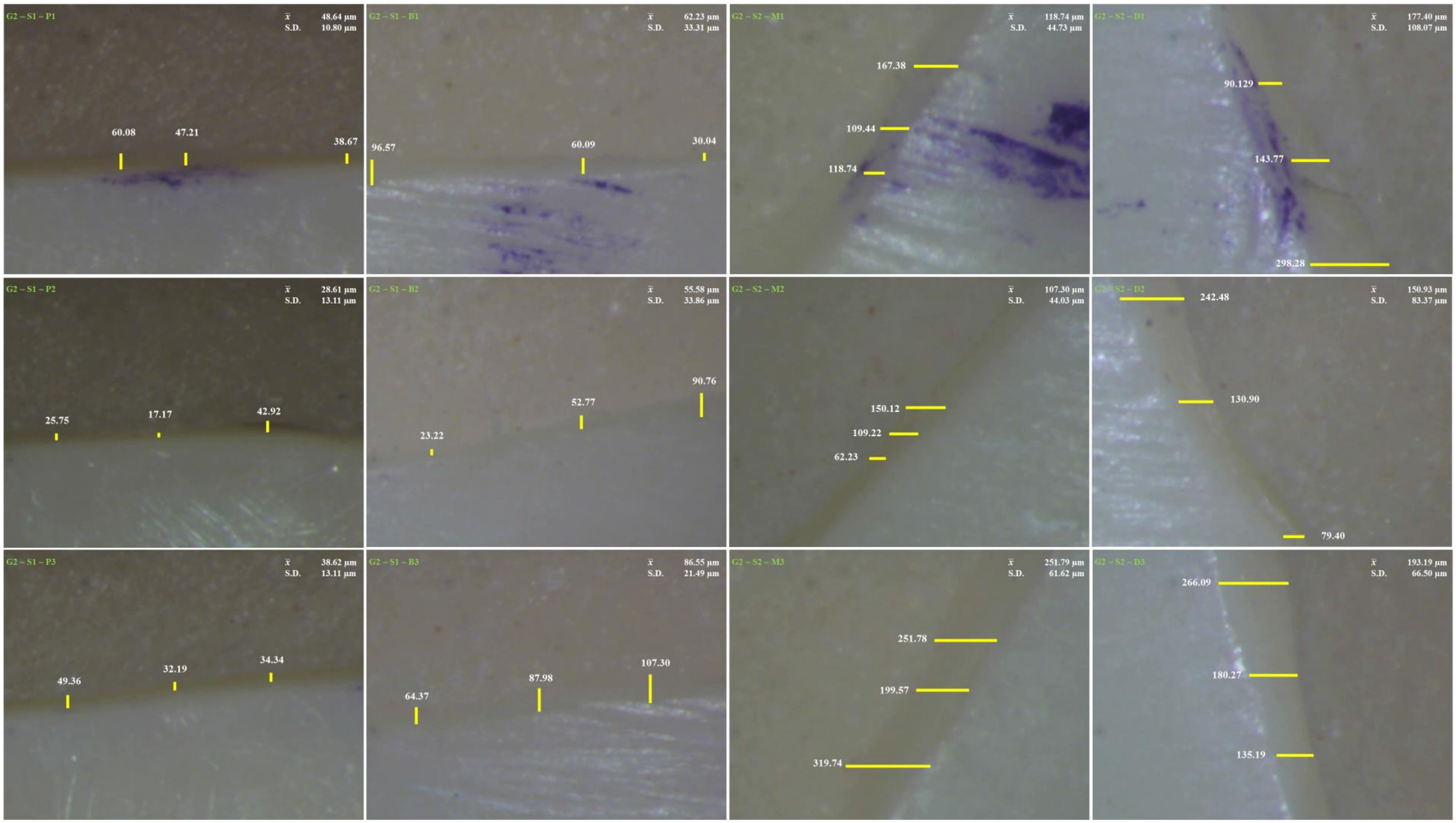


P **B** **M** **D**

APPENDIX C

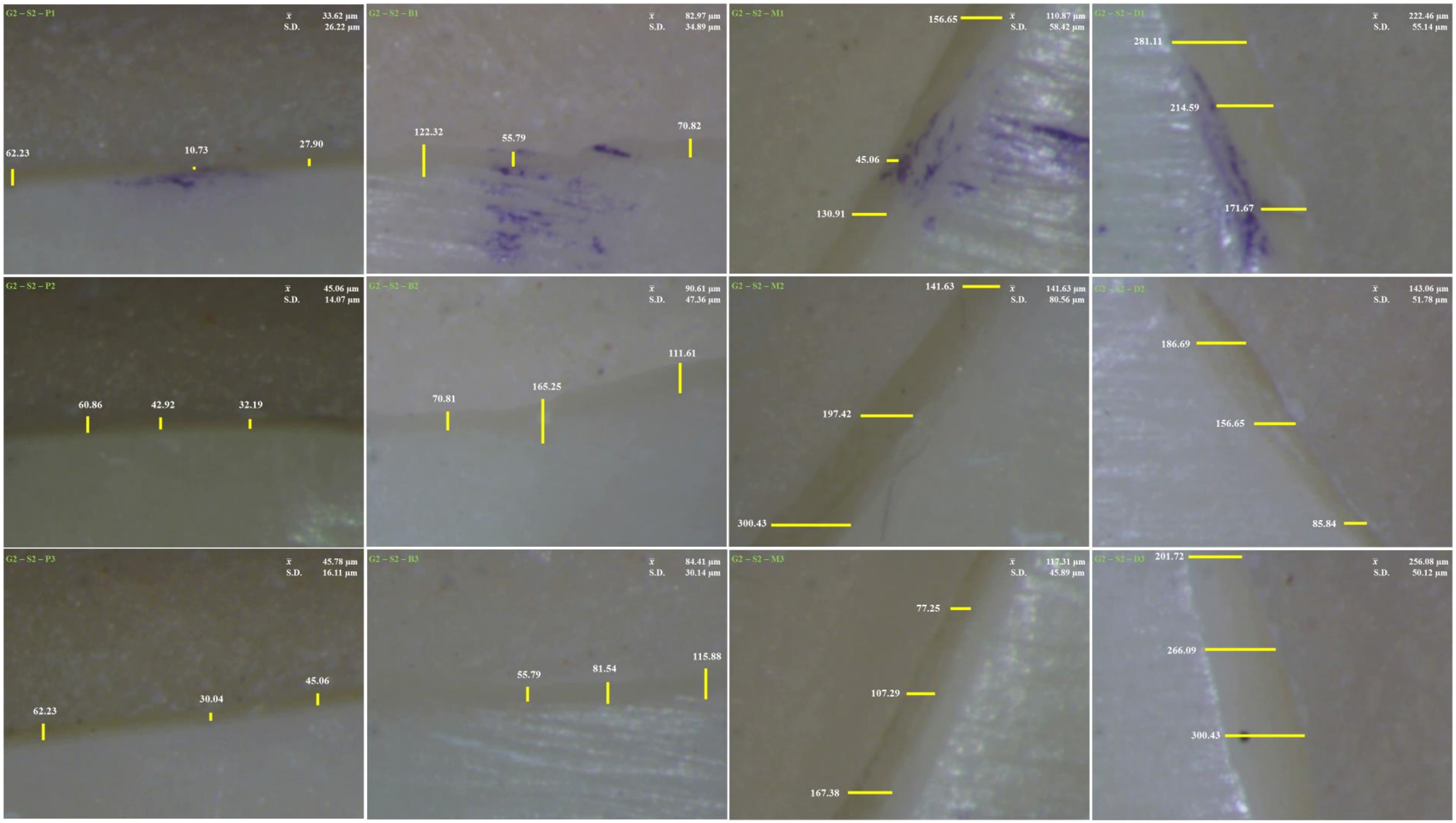
STEREOMICROPE IMAGES – CONVENTIONAL

<u>GROUP 2: SAMPLE 1</u>



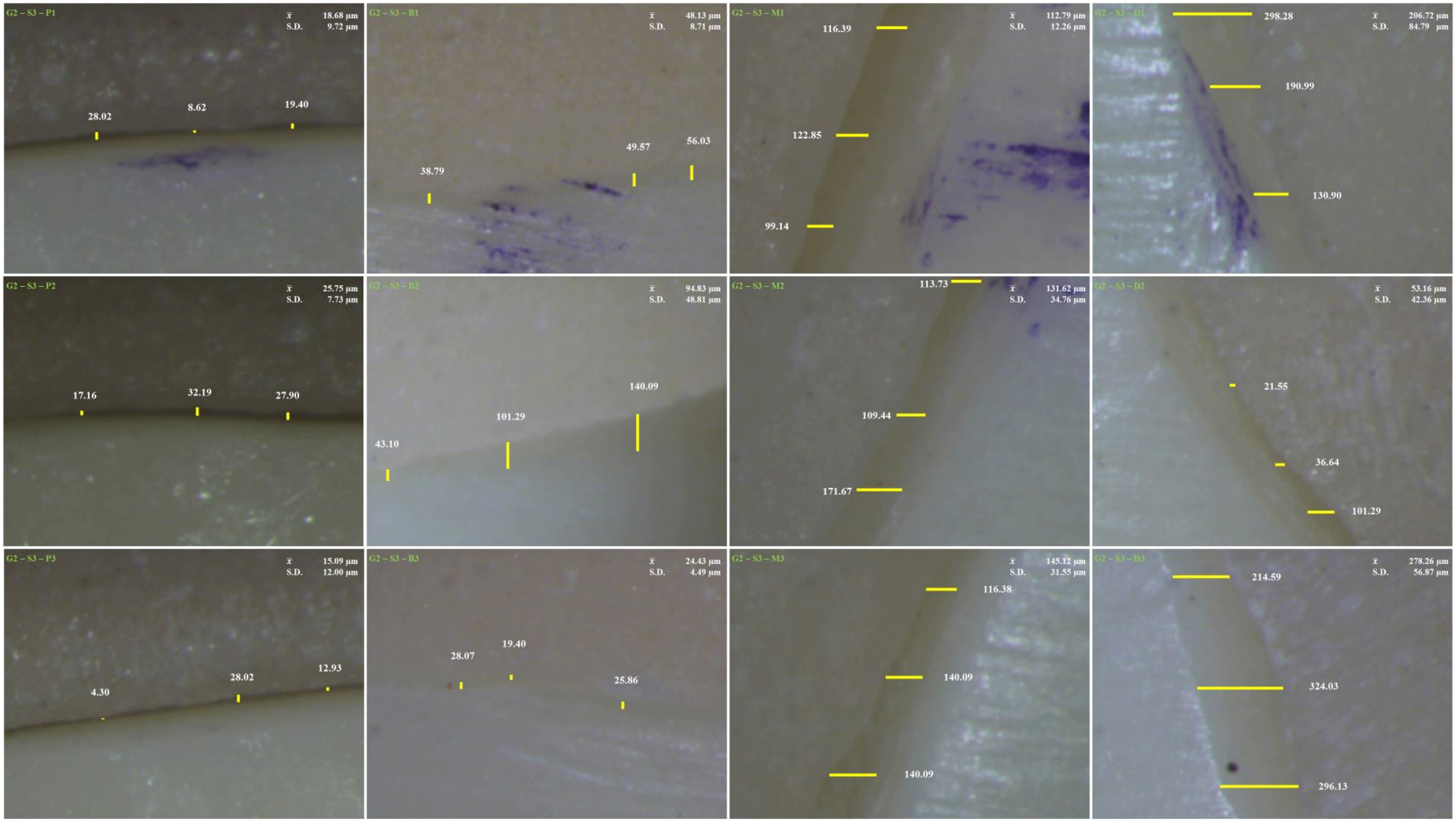
P **B** **M** **D**

GROUP 2: SAMPLE 2



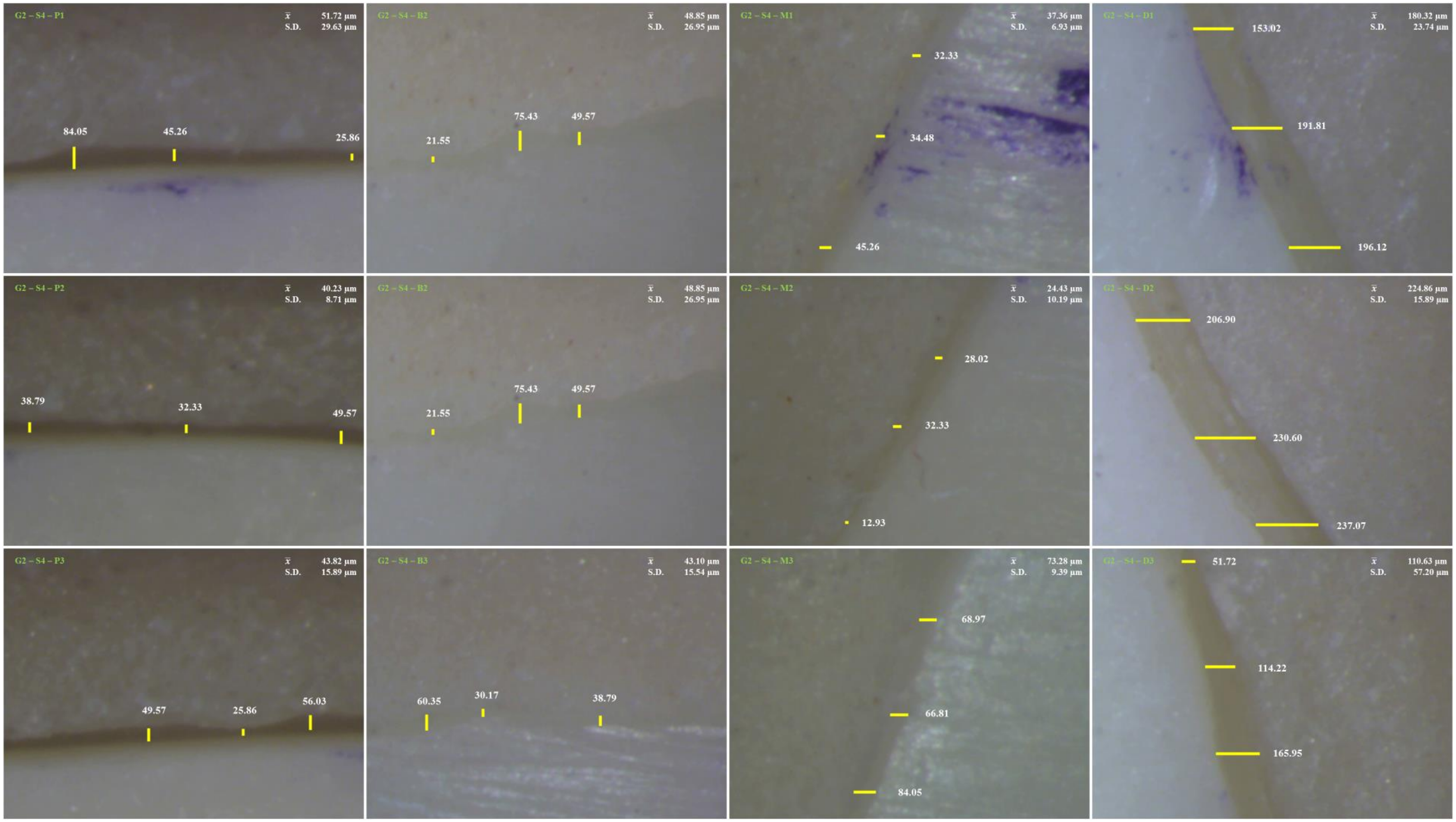
P **B** **M** **D**

GROUP 2: SAMPLE 3



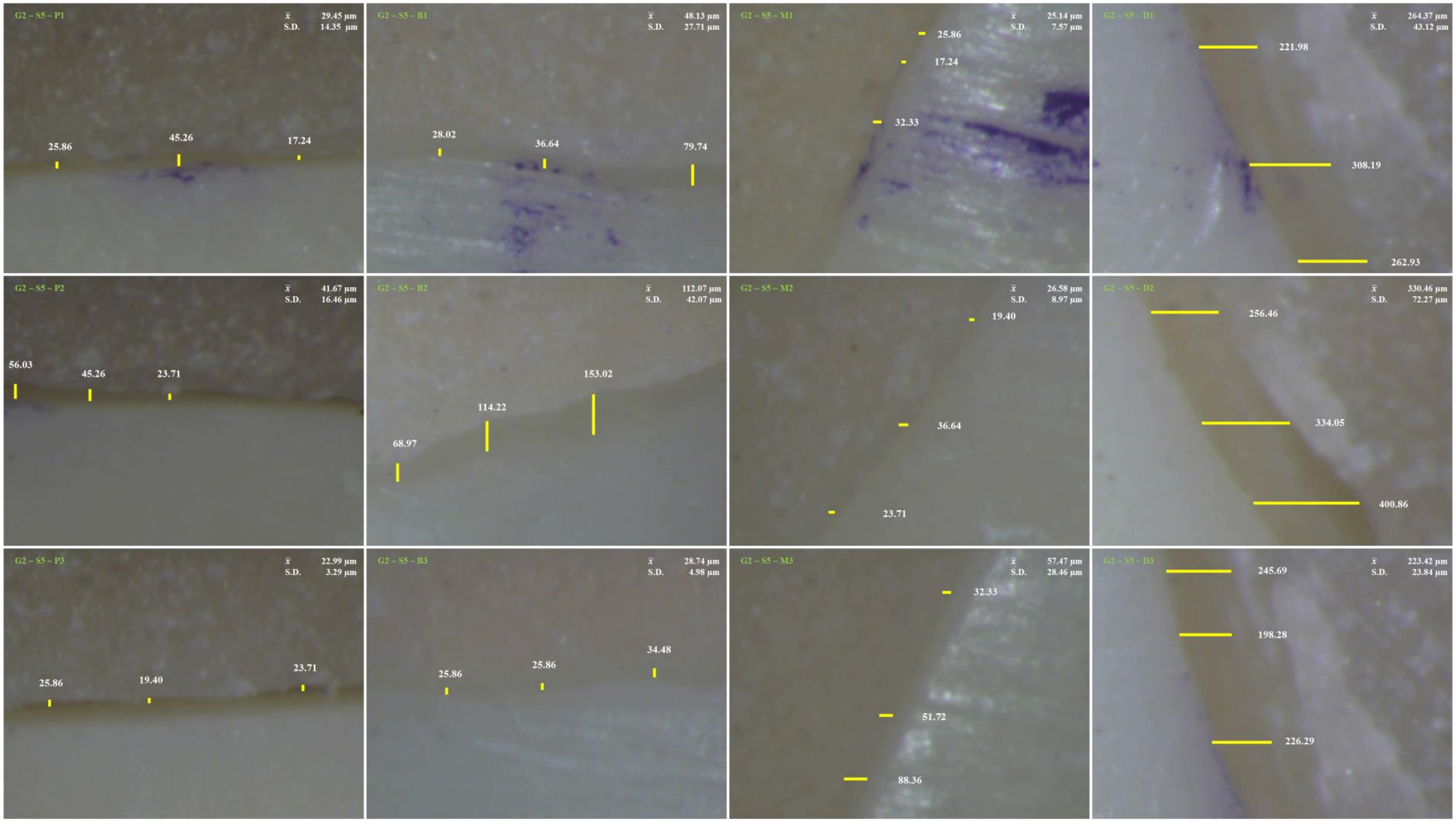
P **B** **M** **D**

GROUP 2: SAMPLE 4



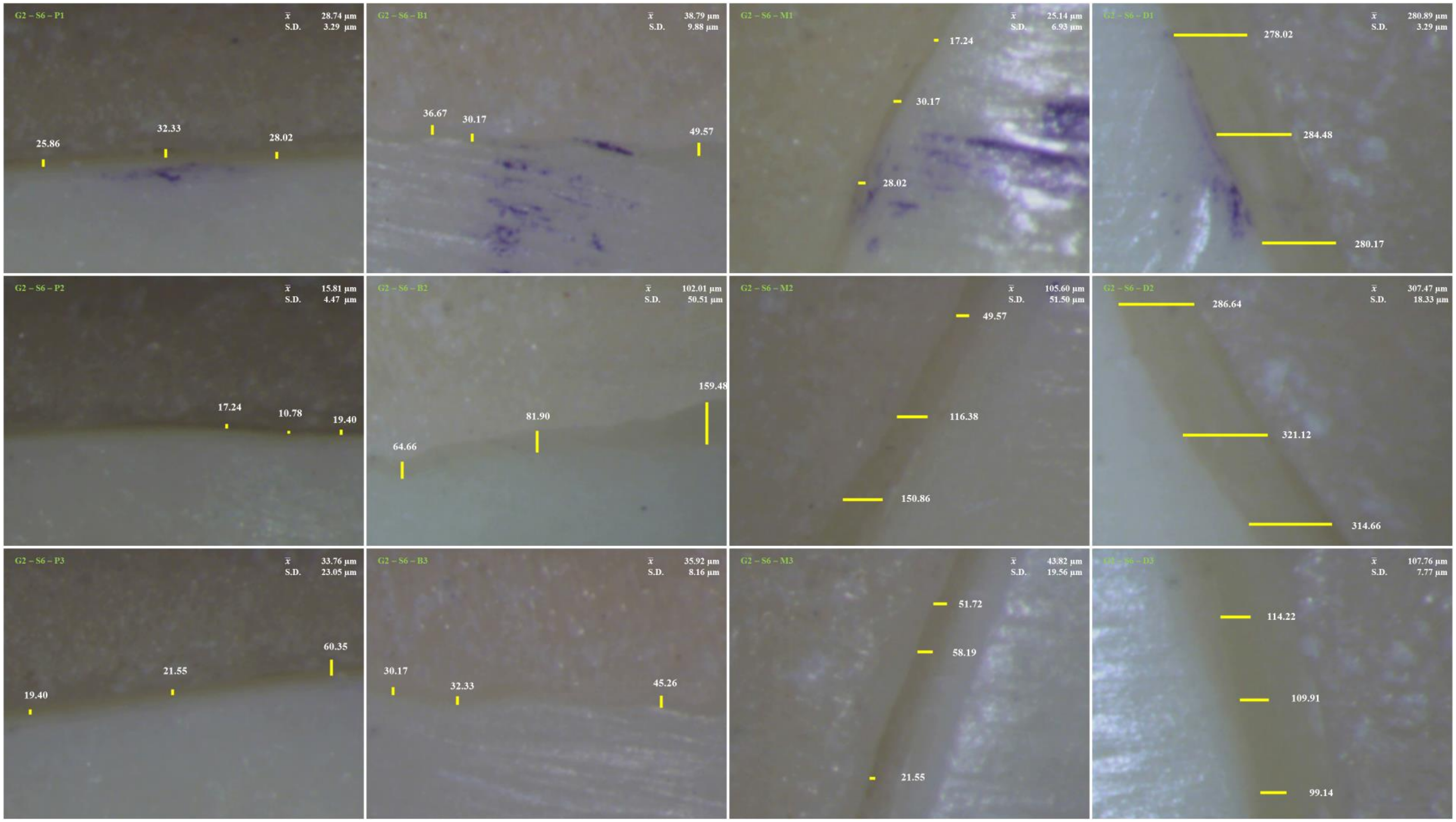
P **B** **M** **D**

<u>GROUP 2: SAMPLE 5</u>



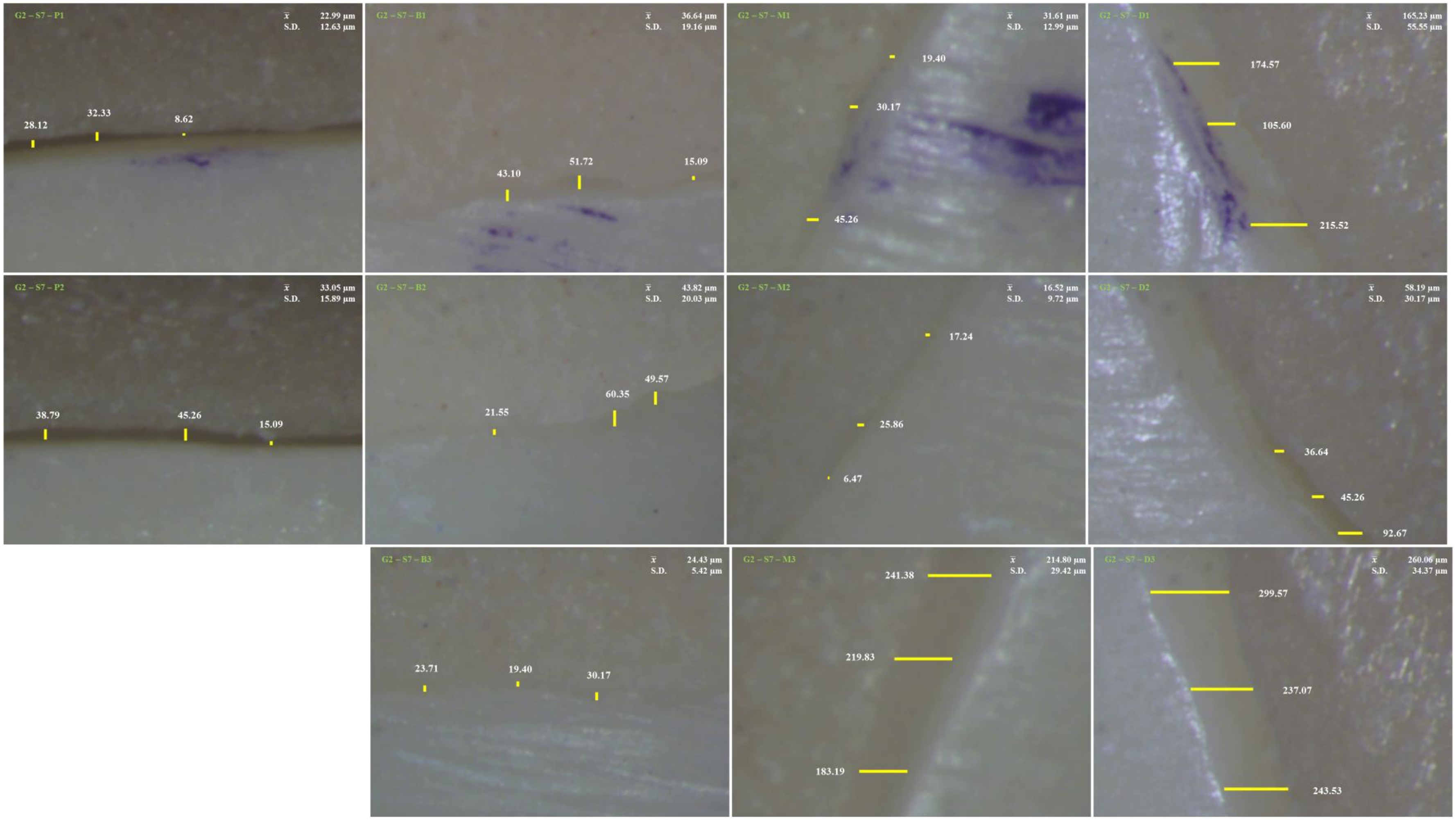
P **B** **M** **D**

GROUP 2: SAMPLE 6



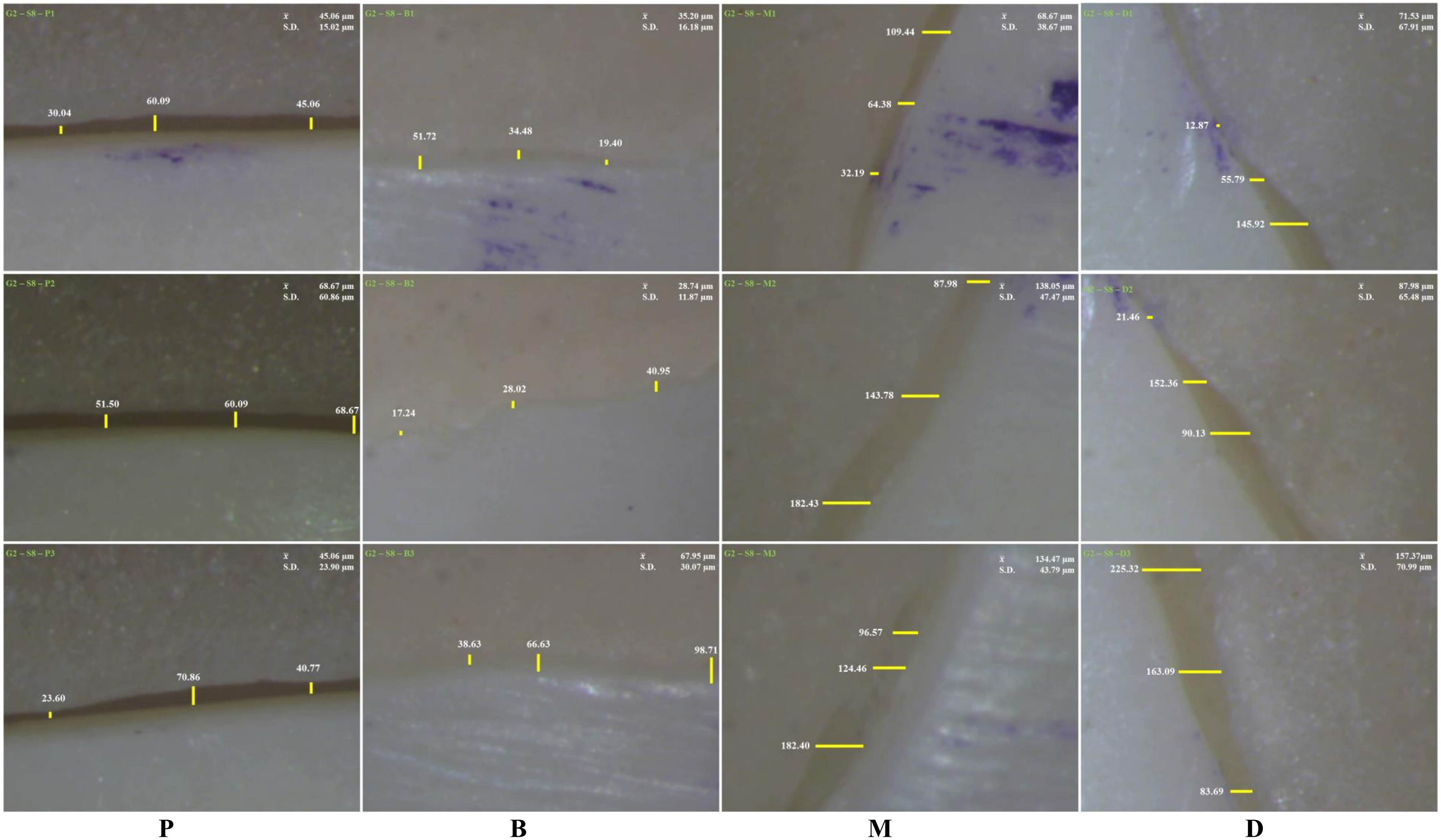
P **B** **M** **D**

GROUP 2: SAMPLE 7

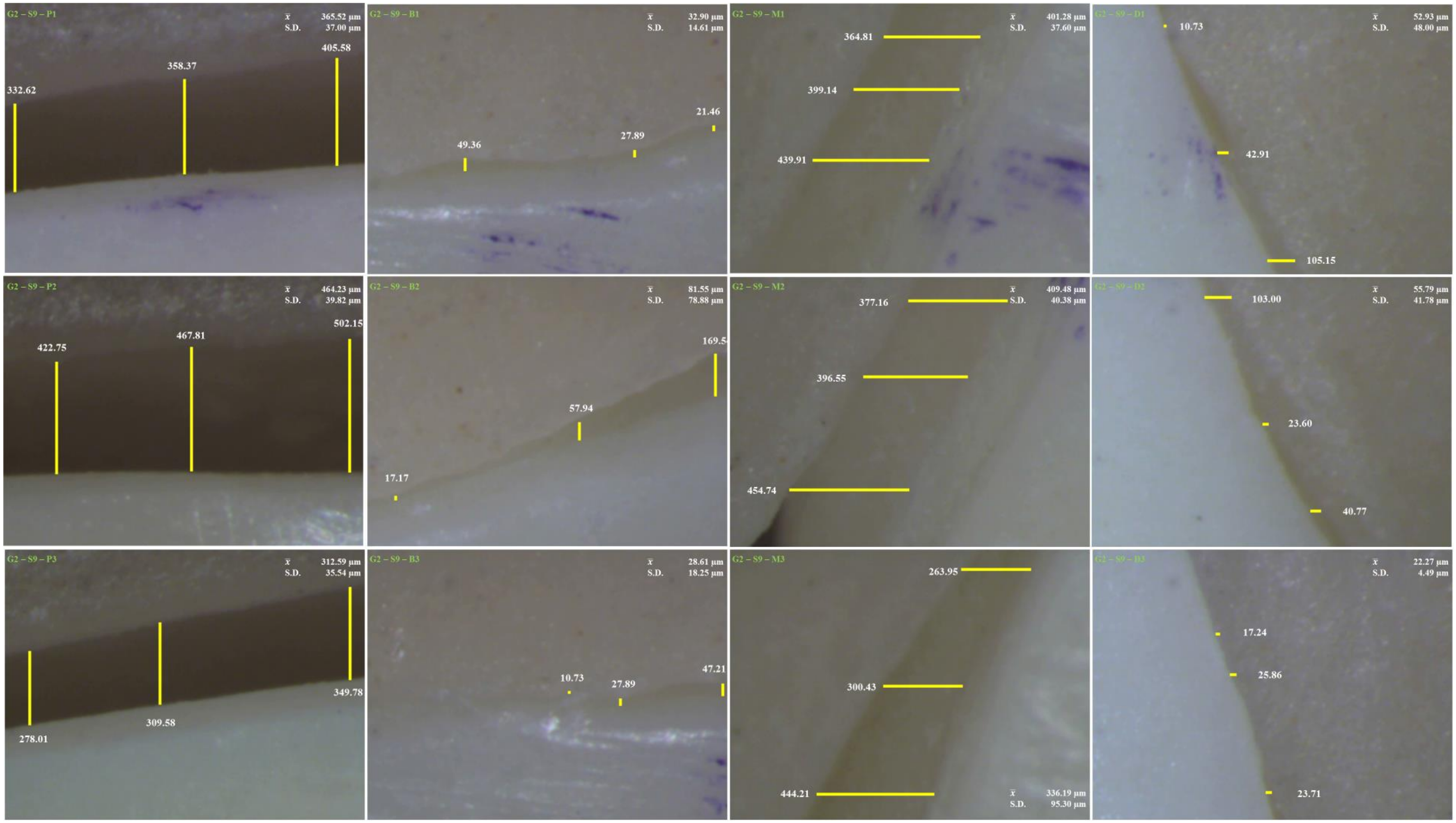


P **B** **M** **D**

GROUP 2: SAMPLE 8

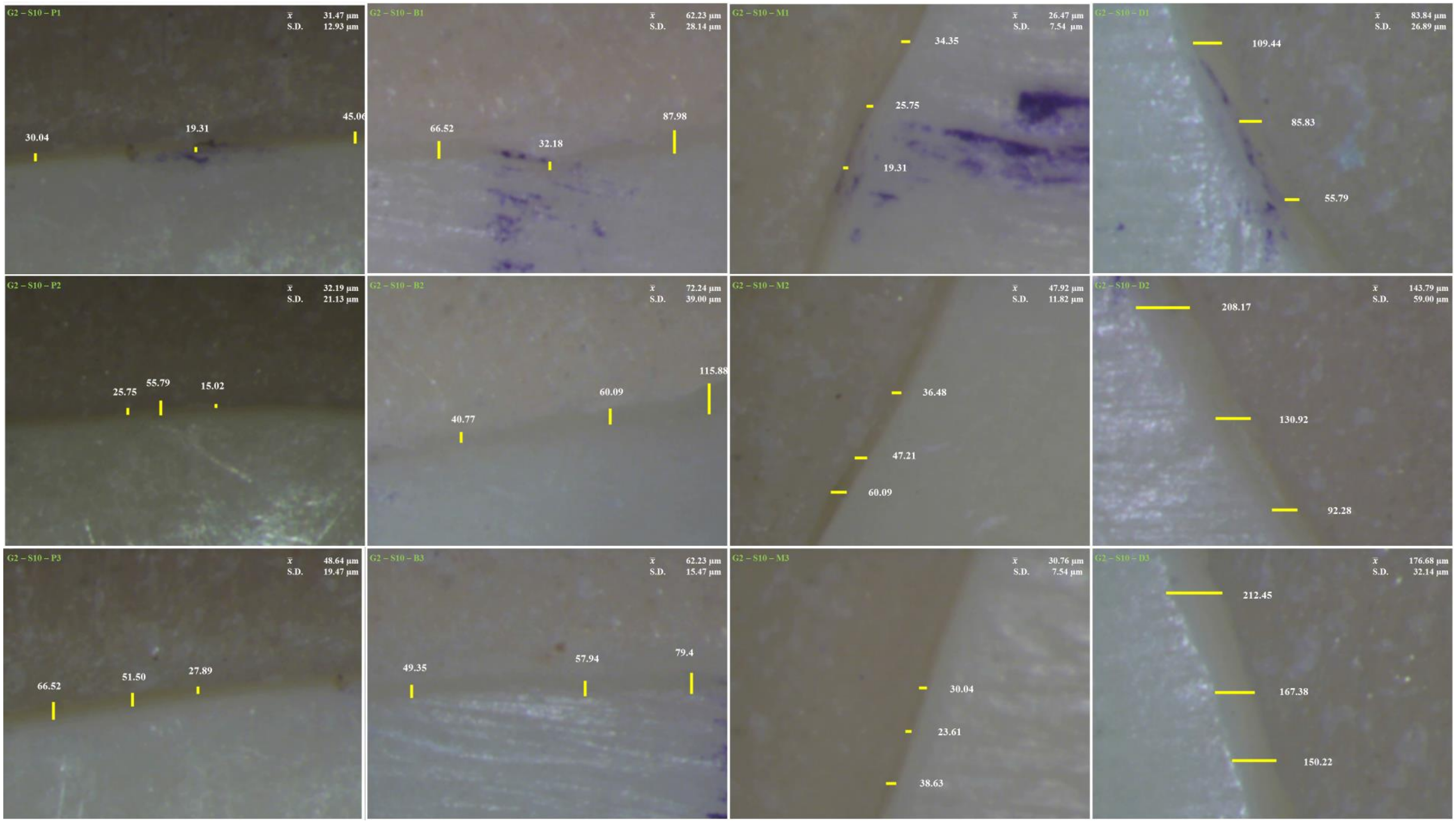


GROUP 2: SAMPLE 9



P **B** **M** **D**

GROUP 2: SAMPLE 10



P **B** **M** **D**

CURRICULUM VITAE
Michael Charles Guzelian
330 West Bloom St • Louisville, KY 40208
978.821.8705 • michael.guzelian@louisville.edu

EDUCATION

University of Louisville, Louisville, KY 2012 – 2015
Master of Science (MS) in Oral Biology May 5th 2015

Georgia Institute of Technology, Atlanta, GA 2008 – 2012
Georgia Tech Honors Program Member
Bachelor of Science (BS) in Biology May 5th 2012
Business Option, Certificate in Biomedical Sciences

Relevant undergraduate and graduate coursework:

Neuroscience, cell biology, biopsychology, cancer biology, biostatistics
Oral immunology, oral microbiology, microbial pathogenesis, microbiology
Biochemistry, systemic physiology, general and oral histology
Gross anatomy, neuroanatomy, endocrinology

RESEARCH EXPERIENCE

University of Louisville School of Dentistry, Louisville KY 2012 – 2015
Clinic Simulation R&D
Thesis: "Comparison of Marginal Fit of Lithium Disilicate Ceramic Veneers Fabricated with CAD-CAM Technology Compared to Conventional Technique"

Research Mentor: Dr. Amirali Zadinejad, DMD, MS
Program Director: Dr. Douglas Darling, PhD
Pending publication – The Journal of Prosthetic Dentistry

UAB School of Dentistry, Birmingham, AL 2011
· Examined ameloblastoma progression through characterization of entire matrix metalloproteinase family
· Relevant skills: qRT-PCR transcription, immunohistochemistry, Western blotting, and gel electrophoresis

Emory University, Division of Cardiology, Atlanta, GA 2010 – 2012
· Organized under W. Robert Taylor, M.D., Ph.D.
· Studied revascularization and blood perfusion from mouse hind limb ischemia
· Developed microencapsulation technique for delivery of mesenchymal progenitor stem cells to tissue injury area
· Surgically removed femoral artery in mice and tracked stem cells through magnetic localization
· Relevant skills: cell splitting, histology, viability assays, enzymatic tracking, flow cytometry, specimen surgery

EMPLOYMENT EXPERIENCE

University of Louisville School of Dentistry, Louisville KY 2014 – present

Dental Clinic Associate – Sterilization

· Insure that all infection control standards are followed according to OSHA and HIPAA guidelines
· Compile instrument packages to be picked up by clinical staff
· Process soiled instrument cassettes and handpieces through entire sterilization process
· Run ultrasonic cleaner to packaging for sterilization to sending through the autoclave
· Maintain high-speed, low-speed, adaptor latch, and nose cone handpieces through specialized oiling process
· Provide surgical set-ups for Oral Radiology and Oral Surgery units
· Set up pre-clinical supplies for dental students to accept lab cases, package and send to labs, and data entry

Cardinal Towne, Louisville, KY 2013 – 2014

Community Assistant

· Boosted sales as a leasing agent for Cardinal Towne during saturated heavy months
· Oversaw and enforced community policies, transferred monthly rent, enacted fees for community violation
· Logged and monitored daily and monthly follow-ups for prospective residents

LA Fitness, Louisville KY 2012 – 2013

Operations

· Provided member service and support related to fitness servicing issues
· Enforced membership account renewal and delinquency
· Issued guest passes with guest and host signed waiver forms into software system
· Transferred monies form guest fees, membership fees, and miscellaneous fees to facility manager
· Checked out equipment, including racquetball reservations, Group Fitness reservations

TEACHING EXPERIENCE

A Better Grade Tutoring, Louisville, KY 2012 – 2014

Academic Tutor

· Provided quality one-on-one tutoring for middle school, high school, and undergraduate students in the Kentuckiana metropolitan school districts:
· Organized lesson plans unique, adaptable, and specific to the students' needs in and out of the classroom
· Established clear expectations every academic semester using monitored time management for coursework, extracurricular activities, and leadership roles
· Determined student's past and current strengths or weaknesses, following curriculum standards set forth by Kentucky Public Schools
· Tracked and evaluated progress of each client to meet or exceed state standard expectations
· Relevant subject matter: Biology, General Chemistry, Geometry, Algebra I and II, Pre-Calculus, Statistics
· Relevant standardized testing: ACT and SAT test-taking preparation

INTERNSHIP EXPERIENCE

Omni Eye Services, Atlanta, GA 2010
Student Intern Ophthalmic Technician
· Organized under Paul Ajamian, Doctor of Optometry & Fellow of the American Academy of Optometry
· Performed various tests for ocular disease in retinal, anterior segment, and glaucoma services
· Expertise in clinical techniques for patients and handled equipment during the diagnosis process
· Observed cataract, vitreous, and trabeculoplasty for clients every Saturday
· Responsible for full-time clinic hours, awarded 100 days of service

Skidaway Institute of Oceanography, Savannah, GA 2009
Field Technician
· Coordinated under Marc Weissburg, Ph.D, Associate Professor, School of Biology
· Collected and cared for experimental blue crabs, whelks, clams, and oysters
· Prepared predator cages, simulated realistic predator-prey models
· Responsible for experimental set-up and maintenance out in the field, full-time position, seven days a week

VOLUNTEER EXPERIENCE

Mathis Dental, Louisville, KY 2013
· Clinic observation for general dentistry and various certifications in prosthodontics, orthodontic, and endodontic procedures
· Totaled 50 hours of shadowing

Atlanta Dental Group PC, Atlanta, GA 2011
· Assists in chair-side dental procedures with Dr. Mark Padolsky, D.D.S, M.A.G.D
· Exposure to cosmetic, implant, and restorative dentistry
· Committed to eight hours every Saturday

Orthodontic Associates, P.C., Haverhill, MA 2010
· Shadowed Dr. Joseph Cardarelli, D.M.D, A.B.O. in pediatric and dentofacial orthodontics
· Learned simple wire-cutting, retainer procedures in dental laboratory
· Totaled 50 hours of shadowing

LEADERSHIP EXPERIENCE

Pi Kappa Phi Fraternity (ΠΚΦ) 2008 – 2012

Honors Program Student Advisory Board
· Selected by Head Honors Program Directors
· Planned Honors Program Expo and Honors program Retreat
· Ensured each entering and graduating class transitioned well into freshman year
· Networked Peer Leaders in Honors residence with Honors Program

Honors Program / Presidential Scholar Activity Board
· Selected by Kari White, President Scholar Academic Advisor

Beta Beta Beta, Biology National Honors Society

GT 1000 Team Leader
· Grading resumes, freshmen presentations
· Mentor for undeclared freshmen to succeed in various aspects of college life

Greek Week Committee
· Planned and organized annual Greek Sing event, Georgia Tech's largest competition for fraternities
· Represented the Interfraternity Council at events incorporating fraternities and sororities

American Medical Students Association

Dental Society at Georgia Tech

PHILANTHROPY SERVICE

International Medical Missions Trip, Cusco, Peru 2011
Volunteering Solutions
· Spent 10 days abroad at a local sister nunnery, assisting children and adults with neurological and orthopedic problems through brushing and flossing
· Engineered cost-effective orthopedic devices out of scratch to address children with severe scoliosis
· Created personal hand splints for finger atrophy
· Diagnosed adults with specific problems under supervision of volunteer doctors
· Formulated a physical therapy routine for a young adult that will regenerate leg strength

International Dental Missions Trip, La Ceiba, Honduras 2012
Volunteering Solutions
· Spent 12 days abroad at central medical center, assisting local dentists with diagnosis of cavities, broken teeth, infected teeth, and missing teeth for 115 patients
· Performed basic teeth extraction from consent of patients
· Discussed with Hospital Chief about oral health standards in Central America
· Gave out tooth brushes for every patient, emphasizing the importance of brushing

Push America Committee
· Pi Kappa Phi national outreach organization: build better leaders tomorrow by serving the disabled today
· Initiated Accessability Wheelchair Ramp Projects, supplied chapter with grant funding to construct ramps for the disabled
· Organized Give-a-Push-Weekend, a project that has helped to make disability centers in metro-Atlanta more accessible

Armenian Relief Society, North Andover, MA
· Educated Sunday School children on the Armenian Genocide
· Lectured on cultural history of the Armenian people
· Served and provided meals for Armenian elders in nursing homes

HONORS & AWARDS

Georgia Tech Honors Program Recipient
· Merit-based scholarship
· Completed four Honors Biology-based courses and three Special Topics courses
· Honors classes require exceptional amounts of work and more stringent grading standards
· Special curriculum over four years that emphasizes active intellectual engagement in students
· Close interaction with faculty in the School of Biology as well as the Honors Program Office

MISCELLANEOUS EXTRACURRICULAR ACTIVITIES

Freelance jazz musician · Alto saxophonist (15 years) · Trumpeter (10 years) · Cartoonist

TECHNICALL SKILLS

Ceramic veneer preparation · digital / conventional impressions
Lava C.O.S. · CEREC · iTero
CERT Trained · Microsoft Office · VPython · ArgusLab · MesreNova · ChemBio 3D Ultra