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Abstract

Title of Thesis: Dimensional Stability of CAD/CAM Patterns: A Longitudinal Study

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The goal of the study was to investigate the accuracy, over time, of computer-aided design and computer-aided manufactured dental patterns fabricated using two different fabrication methods and two materials.

The intaglio surface of the patterns was evaluated at predetermined time periods relative to fabrication time. Surface scans of the generated samples were aligned to the design STL and compared using Geomagic Control X software. Trueness of the patterns were compared at all time points using three-way ANOVA ($\alpha=.05$).

Accuracy of dental patterns deteriorated over time. When materials were considered, wax had better dimensional stability than resin. When fabrication method was considered, milled patterns had better dimensional stability than printed patterns.

Time, material type, fabrication method, and all their interactions, showed a significant effect, however, the difference were small. Thus, both resin and wax CAD/CAM patterns can be used to produce dental restorations with acceptable accuracy.

Dimensional Stability of CAD/CAM Patterns: A Longitudinal Study

by
Shane S. Byun

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Dedication

To my wife, Andie.

My parents, Duke and Mindy.

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Introduction

In today's society, the advancements in medicine and technology have helped improve the average life expectancy. With the increased life expectancy, the past several decades has seen an increase in retention of permanent teeth.¹ As a result, the number of fixed restorations has increased due to functional or esthetic problems, such as decay or fracture.

Fixed dental prostheses (FDP) are typically fabricated indirectly using a physical replica of the teeth. The replica of the teeth are then utilized by the laboratory to fabricate the restoration. With the high number of indirect restorations being made, the dental industry demands methods that are efficient and precise. Advancements in computer-aided design and computer-aided manufacturing (CAD/CAM) technology for the fabrication of restorations has largely increased over the last several years, streamlining processes and creating accurate restorations. Though the majority of CAD/CAM systems are for production of all-ceramic restorations, there are many situations when a metal restoration is required. Traditionally, metal restorations are cast and therefore a pattern for the casting is needed. This pattern was fabricated with preformed wax patterns or hand waxed patterns. CAD/CAM programs can print or mill these patterns which can be integrated into the laboratory workflow. However, there is limited data on the accuracy of CAD/CAM programs and machinery and the dimensional stability of materials used in the fabrication of casting patterns. There is also lack of data on the dimensional stability of CAD/CAM patterns over time. The focus of this study was to evaluate the dimensional stability of CAD/CAM dental patterns.

Conventional Method of FDP Fabrication

After a tooth is prepared for an FDP, a wax pattern is necessary in order to begin the process of fabricating the restoration. The fabrication of the pattern can be completed as a direct method or an indirect method. The direct method consists of fabricating the pattern intra-orally, in the patient's mouth, while the indirect method consists of fabricating the pattern extra-orally, typically in the lab.

The more common method of fabricating an FDP in today's practice is an indirect method as it may provide more advantages than disadvantages. Upon preparing the tooth, the indirect fabrication method starts by obtaining an accurate impression of the prepared tooth. The impression material for an FDP is typically an elastomeric impression material such as polyether or polyvinyl siloxane.² The impression is poured with dental gypsum to produce a physical replica of the teeth. After the gypsum sets, necessary steps are followed to isolate and obtain a replica of the prepared tooth. This replica is called a die. The die is then utilized by the laboratory technician to fabricate a wax-up of the restoration or crown which can be referred to as the wax pattern. The wax pattern is then invested in refractory investment material. After setting, the investment is burned out to remove the wax pattern and to create a negative space necessary for the casting. Then the casting is completed to obtain the restoration. This process of casting the crown is known as the lost wax technique.

Lost Wax Technique

The lost wax technique has been utilized for centuries by artisans around the world as a method for creating metal castings.³ Not until 1907 was the lost wax technique described, for use in dentistry, by William H. Taggart for the creation of gold inlays.³ Taggart

explained his technique, beginning with the use of a special wax, to create the desired form of the final restoration. The wax is invested, melted, and then cast with metal. This method revolutionized dentistry at the time as restorations had not been made as quickly or accurately until then.⁴ A century later, dentistry still utilizes the lost wax technique, in a very similar method as Taggart's, to create metal restorations. Not only is the process labor intensive and time consuming, there are innate characteristics of the materials and methods used in every step of the procedure. These characteristics can create dimensional inaccuracies.

Literature indicates several factors that can affect dimensional inaccuracies of the final restoration. Some inaccuracies are derived from the final restorative material used (i.e. gold). Gold has a tendency to shrink upon casting and cooling. However, there are several other factors that need to be considered: type of stone, water to powder ratios, setting expansion, hygroscopic expansion, thermal expansion, change of temperatures, burnout rate, use of a liner, metal shrinkage, and wax.^{2, 4, 5}

Casting Wax

Of the above factors, wax has particular interest for our study. Although wax is one of dentistry's regularly utilized materials, it is one with the greatest variability. Therefore, a major factor leading to the inaccuracies of casting is the properties of the wax used.⁶ The recommended wax for fabricating an FDP wax pattern is casting wax, per the American National Standards Institute (ANSI) and the American Dental Association (ADA) specification no. 122.⁷ Dental wax used for the lost wax technique is sometimes referred to as inlay wax. It is a specialized wax that has uniform workability over a range of temperatures, can be easily carved without chipping, and can be easily added in layers.²

In addition to these characteristics, casting wax should lack flakiness and be smooth when trimmed or carved, lack residue during burnout, and be dimensionally stable.^{2, 8} Many of these characteristics can be achieved by varying the percentage composition of the various waxes or fillers used to formulate the casting wax.

Casting “wax consists essentially of .”⁹ ANSI/ADA Specification no. 122 classifies waxes into 2 types: type 1 and type 2. Type 1, or casting wax, has a class 1 (soft wax) and a class 2 (hard wax).⁷ Type 2 wax, or baseplate wax, has a class 1 (soft wax), class 2 (hard wax), and class 3 (extra hard wax).⁷ Typically, of the casting waxes, the hard waxes are used for the direct wax technique and soft waxes are used for the indirect wax technique.

As mentioned previously, the direct wax technique is when the wax pattern is fabricated directly on the tooth, in the mouth. However, due to the extremely high coefficient of thermal expansion of wax, it can shrink considerably when transferred out of the mouth into the room temperature. The indirect wax technique utilizes the method mentioned above and the wax pattern is fabricated in the lab. Since the indirect technique is completed outside on a die, in a laboratory setting, this method has the possibility for reduced shrinkage upon setting. However, the shrinkage depends on the thickness of the wax and the time allowed for the wax to set and reach the room temperature.²

Another major challenge with inlay wax is its dimensional change that occurs over time. Just as many materials expand when heated, wax will also expand when heated. As the wax cools, after being melted and formed, stresses develop within the wax. Due to the elastic memory of the wax, the pattern created will distort and contract, with a tendency

to return to its original form.¹⁰ The dimensional stability of the wax pattern can be affected by temperature and humidity and shrinkage can range from 0.3-2.3%.⁶ A study by Fusayama found when patterns were fabricated with a repeated addition wax technique, the wax shrank by .41% and paraffin wax by .35%, 30 minutes after the wax is removed from the die.¹¹ Multiple sources have shown that the dimensional stability of conventional wax is poor and, within 24 hours, will exhibit significant dimensional changes.^{6, 12, 13} The implication of this poor dimensional stability is that once the wax pattern is removed from the die, it must be invested immediately, otherwise the final casting will not fit the tooth preparation. ^{10, 12, 14, 15}

Casting Resins

To reduce dimensional changes over time, resin materials or pattern resins can be used for lab fabricated restorations. The type of resins that can be used for casting are typically auto-polymerized or light polymerized resin. Both types of resins have clinical and laboratory uses. Auto-polymerized resins are often more affordable and easily manipulated but usually require time to polymerize and harden. Light polymerized resins offer some benefits over the auto-polymerized resin (i.e. fast curing, reduced porosity, and possibly less polymerization shrinkage). Of the benefits, Goplana et al indicates that the degree of polymerization shrinkage can be debatable.¹⁶ Overall, pattern resins are beneficial in that once the material is polymerized, it is harder than wax and will be less prone to breaking.

Although resins offer the benefit of being more rigid, there are some concerns with the dimensional stability due to polymerization shrinkage. Historically, polymerization shrinkage in methyl-methacrylate resins was typically found to have a volumetric

shrinkage of 21%, but by utilizing pre-polymerized polymer, the volumetric shrinkage is reduced to about 7%.¹⁴ Studies that evaluated the polymerization shrinkage of auto-polymerizing and light-polymerizing pattern resins found a volumetric shrinkage of 4.5-7.5%.^{17, 18} The amount of shrinkage of resin patterns due to polymerization appears to be more than the shrinkage found in wax when cooling, indicating resins may not be a good option. However, resin patterns, particularly auto-polymerizing resin, may show more shrinkage initially as the material harden, but once polymerized, the shrinkage may be less than wax.^{8, 16} Studies that evaluated the marginal fit and internal adaption have shown that resins, as compared to hand waxing, may have greater accuracy.^{12, 13, 14, 19} With resin pattern material showing better dimensional stability and accuracy than wax, it may be of interest to consider when fabricating patterns for casting.

CAD/CAM Dentistry

With the ability to cure resins, CAD/CAM fabrication methods, such as additive manufacturing, may utilize resins to fabricate patterns. The use of CAD/CAM in dentistry has been increasing and becoming more popular because CAD/CAM offers more efficient, accurate, and consistent production of fixed restorations than conventional methods.²⁰ The fabrication of dental restorations utilizing CAD/CAM technology first began in 1971, by Dr. Francois Duret, who introduced the idea of the fabricating crowns using an optical impression and milling a restoration.²¹ In 1983, he produced the first dental CAD/CAM restoration and went on to develop the Sopher System.²⁰ Dr. Duret's idea was further developed by Dr. Werner Mormann and Marco Brandestini, an electrical engineer.²² Dr. Mormann and Mr. Brandestini develop the first intra-oral scanner, the

Cerec 1.^{20, 21, 22, 23} Since then, there has been great progress with CAD/CAM technology in dentistry.

Digital Work-flow and FDP fabrication method

The many advancements in dental technology have allowed CAD/CAM dentistry to be used in a clinical and laboratory setting. As a result, CAD/CAM dentistry is a reality in everyday dentistry.²⁰ As a smooth and fully digital workflow is achievable, CAD/CAM can help reduce the errors that are introduced by the many factors in the conventional method.²⁰ Although CAD/CAM dentistry was introduced with the idea of fabricating all ceramic restorations, milling metal or laser sintering metal using CAD/CAM technology allows for the fabrication of metal restorations as well.

After the tooth is prepared, the typical workflow for a fully digital sequence starts by scanning the prepared tooth intra-orally as well as the adjacent and opposing teeth. The digital impression produces a digital model on the design software and then a digital design or “wax-up” of the crown can be created. After designing, the all ceramic crown is manufactured by milling a ceramic block.²¹ For a metal restoration, the design can be used to mill metal or laser sinter a restoration.

A combined workflow of digital and conventional can be utilized for fabricating cast restorations. If a conventional impression is made, then the impression can be poured to fabricate the stone model. The stone model can be scanned to replicate a digital model. Then the CAD/CAM process can be initiated followed by the digital wax-up and so forth (as mentioned above). With the progress that has been made with scanners, a conventional impression can now be scanned to produce a digital model and avoid the

need for a stone model. Then, the digital wax-up can be completed, followed by the remaining fabrication steps.

When fabricating a cast restoration, there are many factors that can affect the final fit of the cast metal restoration (mentioned above). Therefore, the use of a physical model and die is often preferred. If a conventional impression was obtained, then a stone model can be poured. If a conventional impression is not available, a physical model could be manufactured with the information available from the digital model. After completing the digital design and wax-up, a physical replica, or pattern, of the digital wax-up can be fabricated for investment and to complete the casting.

Subtractive and Additive Manufacturing

The CAD/CAM fabricated pattern can be obtained by means of milling (subtractive manufacturing) or printing (additive manufacturing) wax or resin pattern. Computer-aided manufacturing can be categorized into subtractive and additive manufacturing. The start of digital dentistry utilized subtractive manufacturing, often times referred to as milling, which incorporates cutting away to obtain the final object. Typically, the subtractive manufacturing method requires a block or puck of the working material to be present. This material is then cut down until the desired object is obtained. Subtractive manufacturing, or milling, is continuing to expand and develop in the world of digital dentistry. However, a major disadvantage of subtractive manufacturing is the waste of excess materials and the inability to reuse materials that have been cut away. This disadvantage can produce economic and environmental burdens.²⁴ Another limitation to subtractive manufacturing is the inability to machine and cut away on undercuts or areas the milling bur cannot access.²⁴

Unlike subtractive manufacturing, additive manufacturing produces the object by adding and building up the object by using a light or laser source to selectively join the material.²⁵ The types of additive manufacturing that currently exist are: fused deposition modeling (FDM), selective laser melting (SLM), selective laser sintering (SLS), ink jet modeling (IJM) and stereolithography apparatus (SLA); sometimes simplified as printing.²⁵ SLA will be the method of fabrication used in this study.

Regardless of the manufacturing method, accuracy is an important factor. By removing some of the factors of the conventional technique that introduce inaccuracies, digital dentistry could help produce accurate restorations.

However, because the applications of these technologies for dental purposes is relatively recent, there are still questions about the accuracy of what these CAD/CAM systems produce. A paucity of literature has investigated the performance of CAD/CAM patterns, utility, accuracy, and dimensional stability. Bhaskaran et al. compared marginal and internal gap of direct metal laser sintered copings to copings cast from SLS printed wax patterns and conventional hand-wax patterns.¹⁹ Overall, they found that marginal gap was significantly greater on the conventional cast copings than the printed wax copings and SLA copings. Although SLA had a significantly smaller marginal gap compared to the cast copings, the internal gap was the largest, without significance. Bhaskaran showed CAD/CAM fabrication could produce accurate and clinically acceptable copings whether printed patterns were cast or copings were fully CAD/CAM fabricated.¹⁹ In another study by Park et. al., three digital methods of fabricating CAD/CAM patterns and conventional hand-waxing patterns were compared.²⁶ They found a significantly improved internal gap by micro-SLA over all other CAD/CAM methods but not the conventional wax

technique. No significant difference was found in the marginal gap amongst all methods. It was concluded that all methods are clinically acceptable for the production of dental restorations.²⁶

Fathi et al. compared conventional, milled, and printed CAD/CAM methods and evaluated the accuracy of the final restorations cast from the created patterns.²⁷ Fathi found that printed patterns had the most accurate fit.²⁷ Shamseddine et al. investigated the marginal and internal fit of pressed ceramic crowns made from milled patterns and conventional hand-wax patterns.²⁸ They reported a significant decrease in the marginal gap and significantly improved fit on the crowns made from the CAD/CAM patterns.²⁸

As indicated by the limited number of studies, CAD/CAM patterns appear to produce as good as or a better fit than conventional patterns. In regards to additive vs subtractive manufacturing, it appears that additive manufacturing may have better accuracy. A more recent study by Bae et al compared additive (SLA and SLS) and subtractive manufacturing methods and found that overall, additive manufacturing had better accuracy than the subtractive method.²⁴

As reported above, the methods of fabrication have a significant effect on the dimensional stability of a crown. Of the studies reported above, additive manufacturing appears to be both superior and more accurate than subtractive manufacturing.^{24, 27} When it comes to additive manufacturing, many in-office or smaller dental labs may only have SLA or resin printing capabilities. With the growth of additive manufacturing using resins, more studies are needed that compare the accuracy of additive vs subtractive manufacturing and the materials used (i.e. resin and wax). For casting purposes and

technique, the various computer-aided manufacturing methods utilize both wax and resin products.²⁶ More studies are needed regarding the dimensional stability, over time, of CAD/CAM patterns and whether the material and method of fabrication have an effect on dimensional stability.

In this study, we discuss dimensional stability in terms of trueness or accuracy.

Dimensional stability is defined by the Glossary of Prosthodontic Terms as “the ability of a material to retain its size and form.”²⁹ A material that is able to maintain its size and form would be deemed dimensionally stable. When patterns are designed and manufactured by CAD/CAM technology, the patterns fabricated must replicate the dimensions of its design in order to be deemed dimensionally stable. The pattern being dimensionally stable would mean it is accurate.

Although the International Organization for Standardizations (IOS) states that accuracy is assessed by both trueness and precision, our study looked at trueness but not precision. Trueness was defined by the IOS as the deviation from the actual dimensions.^{30, 31} This study evaluated trueness by comparing the root mean square (RMS) of the scanned samples to the actual dimensions of the reference design file.³⁰ RMS is typically calculated by obtaining the square root of the mean square of the positive and negative deviations between the sample and the reference.²⁴ RMS in this study was calculated by Geomagic Control X (3D Systems; South Carolina, USA). The RMS values were used to help indicate if the patterns have superior trueness or accuracy. These terms are interchangeable.

Purpose

Dimensional stability of patterns for a three-unit FDP was tested utilizing various types of materials used for CAD/CAM patterns. The first purpose of this study was to investigate the dimensional stability, in terms of trueness, of CAD/CAM dental patterns over time (zero minutes, 20 minutes, 24 hours, one week, and two weeks). The second purpose of this study was to compare the trueness of two CAD/CAM materials (resin and wax, Table 1). The third purpose of this study was to compare the trueness of the two CAD/CAM fabrication methods (additive and subtractive, Table 2).

Table 1. Materials Tested

Type	Material Name	Manufacturer	Method of Fabrication
Resin	Castable Resin	Formlabs, Inc	Printing/Additive
Wax	Castable Wax Resin	Formlabs, Inc	Printing/Additive
Resin	Vericore PMMA Ivory	Whip Mix	Milling/Subtractive
Wax	Vericore Wax	Whip Mix	Milling/Subtractive

Table 2. CAD/CAM Fabrication Methods.

Fabrication Method	Machine	Manufacturer	Materials to be used	XY - Resolution
Additive: Printing (SLA)	Form 2	Formlabs, Inc	Castable Resin and Castable Wax	150 micron ³²
Subtractive: 5-axis milling	DWX-51D	Roland DGA Corporation	Vericore PMMA Ivory and Vericore Wax	TBD

Hypotheses

Null Hypotheses

1. The amount of time that has passed after fabrication of a pattern will not have a significant effect on the dimensional stability of the patterns.
2. The type of material used to fabricate the pattern will not have a significant effect on the dimensional stability of the patterns.
3. The method used to fabricate the pattern will not have a significant effect on the dimensional stability of the patterns.
4. There is no significant interaction between time and type of material on the dimensional stability of the patterns.
5. There is no significant interaction between time and method of fabrication on the dimensional stability of the patterns.
6. There is no significant interaction between type of material and method of fabrication on the dimensional stability of the patterns.
7. There is no significant interaction between time, type of material, and method of fabrication on the dimensional stability of the patterns.

Research Hypotheses

1. As the amount of time increases after fabricating a pattern, the dimensional stability will significantly decrease.
2. Patterns fabricated in resin will have significantly better dimensional stability than patterns fabricated in wax.
3. Patterns fabricated by the additive method will have significantly greater dimensional stability than the subtractive method.
4. There is a significant interaction between time and type of material on the dimensional stability of the patterns.
5. There is a significant interaction between time and method of fabrication on the dimensional stability of the patterns.
6. There is a significant interaction between the type of material and method of fabrication on the dimensional stability of the patterns.
7. There is a significant interaction between time, type of material, and method of fabrication on the dimensional stability of the patterns.

Materials and Methods

To gain a better understanding of CAD/CAM materials used in dentistry, this study sought to evaluate dimensional stability in terms of trueness or accuracy. Dimensional stability was defined in the Glossary of Prosthodontics Terms as the “ability of a material to retain its size and form.”²⁹ Trueness was defined by Ender and Mehl as the deviations of the scanned samples when compared to the actual measurement of the reference, the original design file.³⁰ In this study, the dimensional stability, or trueness, was measured by root mean square (RMS) by comparing the scanned samples to the actual dimensions of the reference design file.³⁰ RMS was obtained from the calculations provided by the Geomagic Control X software. If the RMS value is lower, the patterns will be deemed to have superior dimensional stability or trueness. For this study, trueness was interchangeable with the term accuracy.

The first purpose of this project was to investigate the dimensional stability, over time, of patterns fabricated by CAD/CAM, in terms of trueness or accuracy.³³ Accuracy was measured at multiple times (0 minutes, 20 minutes, 24hours, 1 week, and 2 weeks) by comparing the scanned CAD/CAM pattern, at each time period, to the reference file (original design file) used to print and mill the patterns. The allotted times had a ten-minute buffer due to the difficulty of scanning each sample at the given time period. The RMS values provided by the software were presented in millimeters, but were converted to micrometers due to the low values calculated.

The second purpose of this project was to investigate the accuracy of the CAD/CAM dental pattern by type of material (resin or wax). Accuracy (by type of material) was

measured by comparing the scans of the CAD/CAM dental patterns to the reference design.

The third purpose of this project was to investigate the accuracy of the CAD/CAM dental pattern by method of fabrication (subtractive or additive). Accuracy (by method of fabrication) was measured by comparing the scans of the CAD/CAM dental patterns to the reference design.

As shown in Table 1, the resin-based materials used for this study were Castable Resin by Formlabs, Inc., and Vericore PMMA Ivory by Whip Mix. The wax based materials were Castable Wax Resin by Formlabs, Inc. and Vericore Wax. Machines used were the Formlabs Inc for additive manufacturing (printing) and DWX-51D for subtractive manufacturing (milling) – see Table 2.

FDP Preparation

One typodont dental model (Nissin Dental Products, Kyoto, Japan) was prepared with a Brasseler round-end taper super-coarse diamond (#LGI5850) and then refined with Brasseler round-end taper fine diamond bur (#LGI8850) by the principal investigator (SB) for a three-unit FDP from #19-21, with tooth #20 removed from the typodont and the vacant space filled with pink baseplate wax. The design of the preparations included a chamfer margin (.5 mm), an axial reduction (.5 mm), an occlusal reduction (1 mm of non-functional cusp and 1.5mm over the functional cusp), and a ten-degree taper.³⁴

Digital Acquisition and Design

The typodont was scanned with the D2000 Dental Lab Desktop Scanner (3Shape; Copenhagen, Denmark). Both arches of the typodont were scanned at once. The scan was then imported to the digital design software, Dental System™ (3Shape), and the digital

wax-up of the FDP was designed and saved as an open source standard tessellation language (STL) file format. The parameters used when designing the FDP are in Figure 1. This saved file served as the reference design used to produce CAD/CAM dental patterns and to compare the subsequent scans.

3 Shape Cement Settings	
<i>Cement gap</i>	0.04 mm
<i>Extra cement gap</i>	0.07 mm
<i>Distance to margin line</i>	0.08 mm
<i>Smooth distance</i>	0.02 mm

Figure 1. Cement Space Parameters Used for Designing FDP Abutments

Production of Additive Manufactured Patterns

The Form 2 SLA 3D Printer (FormLabs, Inc., Table 2) was used for printing a group of Castable Resin and Castable Wax patterns. The printing method is an additive manufacturing method. The printer utilizes stereolithography to print items at layer thicknesses of either 25 microns, 50 microns, or 100 microns. To account for the requirement for dentistry’s high level of accuracy and the time to fabricate the patterns, the patterns were printed at 50 microns. The design file from Dental System™ (3Shape) design software was imported into the Formlab software program. The pattern was oriented to the print deck with the occlusal surface of the pattern being parallel to and facing the print deck, as recommended by Formlabs. Printing supports were added per Formlabs automatic print support generator. Each time, a maximum of three patterns in the selected material was printed on the build platform to minimize variables that might be introduced while the pattern is waiting to be scanned and to reduce time of printing.

The print format of the initial three patterns were saved and reused to print the remaining samples.

After printing, the patterns were removed from the build platform. Both the Castable Resin and Castable Wax Resin patterns were first agitated in a 90% isopropyl alcohol (IPA) bath and then submerged in the same bath for ten minutes. Upon removal from the first bath, the patterns were agitated in a second IPA bath and then submerged for an additional five minutes (Castable Wax Resin) and ten minutes (Castable Resin). After thorough rinsing, the Castable Wax Resin patterns were ready for scanning. The Castable Resin patterns were post-cured in a light curing box (Curebox, CB-4051) for 120 minutes at 45° C to complete the polymerization process. A total number of 12 Castable Resin patterns and 12 Castable Wax patterns were printed (Figure 2).



Figure 2. Additive Manufacture Patterns: Intaglio surface of patterns fabricated by additive manufacturing -- (a) Castable Resin, (b) Castable Wax. Sprues were not removed due to only analyzing intaglio surface.

Production of Subtractive Manufactured Patterns

The DWX-51D 5-axis mill (Roland DGA Corp., Table 2) was the subtractive CAD/CAM manufacturing method used for milling the Vericore Wax and PMMA Ivory patterns.

This mill utilizes disks that are milled to the STL file designed and described in the digital acquisition section. The patterns were oriented on the wax or PMMA billet and a total of five sprues were added, two on #18, one on #19, and two on #20. The pattern with the positioned sprues was copied and pasted to keep the sprue attachment on the same axial surface. Minor changes in the angulation of the sprue was made for optimal sprue position. A maximum of three patterns in the selected material was milled. After milling, the patterns were removed from the billet, sprues were sectioned using straight nose carbide bur (Brasseler #H259.11.010), and the surfaces of the pattern to which the sprues were attached were smoothed with a straight nose fine carbide bur (Brasseler #H257EF.11.060). A total of 12 FDP Vericore Wax patterns and 12 FDP Vericore PMMA Ivory patterns were milled on their corresponding billet (Figure 3).

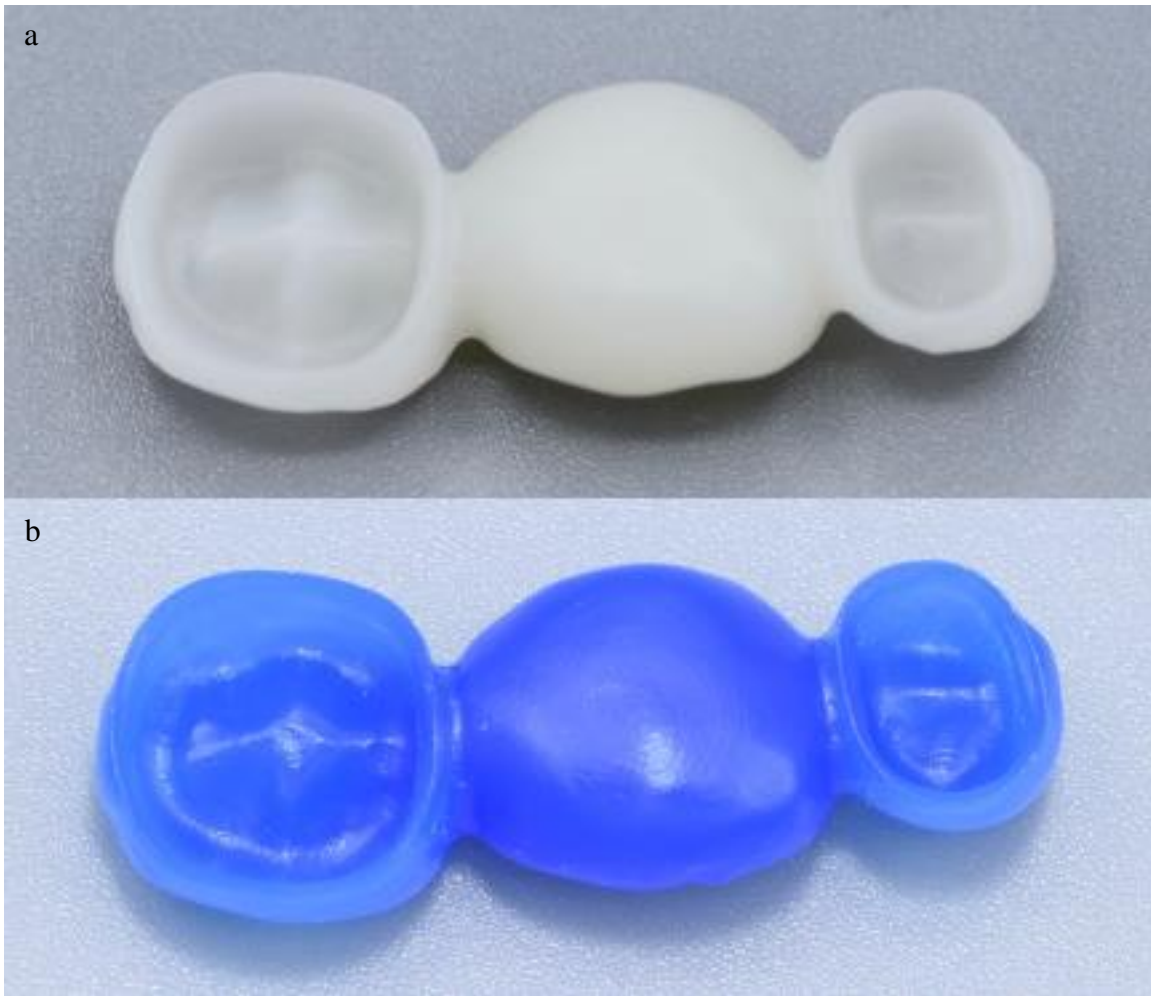


Figure 3. Subtractive Manufactured Patterns: Intaglio surface of patterns fabricated by subtractive manufacturing after removal from billet and sprues -- (a) Vericore PMMA Ivory, (b) Vericore Wax.

Experimental Procedures and Data Collection

After fabricating the CAD/CAM dental patterns, each pattern was sprayed with scanning powder (Sirona Cerec Scan Powder) and then scanned immediately within 0 to 10 minutes of the above described times. These scans were used to compare the accuracy of the printing and milling fabrication method. Patterns in all groups were labeled and stored in a labeled container.

Each pattern was scanned with the D2000 Dental Lab Desktop Scanner (3Shape) at the assigned, subsequent time periods. Due to the study only evaluating the intaglio surface of the patterns, the sprues were not removed from the printed patterns. By keeping the sprues, it allowed the patterns to remain upright and consistent scans of the intaglio surface could be obtained. The milled patterns were fixated with 3 Shapes Scan Fix Putty and a metal wire. The data was then imported into Geomagic 3D Compare Software (3D Systems, Inc.).^{33, 35, 36, 37, 38}

All subsequent scans of the patterns were compared to the reference design (STL file) using the Geomagic Compare Software. After importing the scanned data and reference design into Geomagic, the intaglio surface of the reference design was outlined. The outline was slightly beyond the FDP margin, incorporating part of the cameo surface. The subsequent scans were aligned to the reference design's intaglio surface using the software's "best fit alignment" algorithm (Figure 4). The software's "3D compare" option was utilized to compare the dimensional stability. The "3D compare" provided a plus or minus deviation and RMS value between the reference scan and subsequent scan.^{33, 35, 36, 37, 38} The data, measured in millimeters, were collected in terms of RMS. The differences were recorded for each group and then compared to assess the dimensional change, over time, of the patterns in terms of trueness.

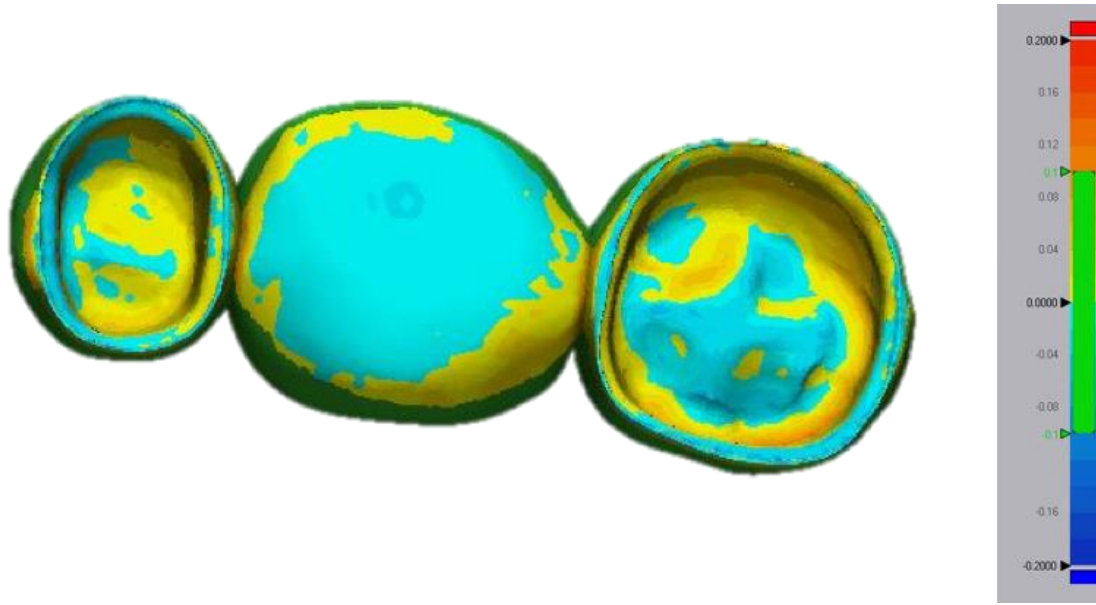


Figure 4. Alignment of Reference and a Sample File: Sample alignment and comparison of reference and sample on Geomagic Control X showing positive and negative deviations.

Sample Size and Groups for Patterns

There were a total of five time periods at which the patterns were scanned, two methods of fabrication, and two types of materials. A total of 24 additive manufactured patterns, 12 in resin and 12 in wax, were fabricated. A total of 24 subtractive manufactured patterns, 12 in resin and 12 in wax, were fabricated. All patterns in the experimental groups were created by machine.

Pilot Study

A pilot study was conducted to help determine the number of subjects. The pilot study lead to a clarification of the methods and protocol for the research study. Initially, the study was planned for a two-way ANOVA because type of material and method of fabrication were combined into one group, named material. This material group had four materials: printed resin, printed wax, milled resin, and milled wax. However, this method of analysis did not allow for the use of data to compare the dimensional stability of additive vs subtractive manufacturing. Therefore, a decision was made to separate the type of material and method of fabrication. This created three independent variables for the actual study.

Power Analysis

It was planned that a post hoc power analysis would be used to determine if the study had a sufficient number of subjects.

Statistical Analysis

Three-way Analysis of Variance (ANOVA) was used to evaluate the accuracy of time, type of material, method of fabrication, and their interactions. A Tukey test was used to check for a significant difference between the five time periods. To make the number of subjects feasible for a resident's study, a small sample size with an n of 12 in each cell was chosen. A $p \leq .05$ was considered significant.

Results

There were five time periods, two material types, and two fabrication methods. An n of 12 was used for each material (Castable Resin, Castable Wax, Vericore PMMA, Vericore Wax), for a total n of 48 patterns in each time period and 240 patterns when all time periods were combined (Table 3). There was a total of 240 patterns when categorized by type of material and a total of 240 patterns when categorized by method of fabrication.

The total N of this study was 720.

A three-way ANOVA revealed significant differences in all three main effects (time, material, and fabrication method) and their interactions. Power analysis showed significant number of subjects for all analyses except that of the interaction between time and method of fabrication (Table 3).

Table 3. Three-Way ANOVA Table Showing Differences in Dimensional Stability for Time, Material, and Method

	Patterns (n)	Mean	St. Dev	Df	F	p	Observed Power
Time							
20 minutes	48	29.44 _a	12.58	4	5.303	≤.0005	.970
24 hours	48	29.87 _a	13.02				
0 minutes	48	29.94 _{ab}	12.88				
2 weeks	48	32.59 _{bc}	13.99				
1week	48	32.72 _c	13.70				
	Total=240						
Material							
Wax	120	27.53	11.04	1	118.272	≤.0005	1.000
Resin	120	34.30	14.34				
	Total=240						
Method							
Subtractive	120	19.47	4.72	1	1351.627	≤.0005	1.000
Additive	120	42.36	8.01				
	Total=240						
Time x Material				4	3.630	≤.007	.872
Time x Method				4	2.623	≤.036	.729
Material x Method				1	43.139	≤.0005	1.000
Time x Material x Method				4	3.715	≤.006	.880
	Total N = 720						

The Effect of Time on Accuracy

The amount of time that passed from fabrication significantly affected the accuracy of the patterns fabricated ($F=5.303$, $p \leq .0005$). The time periods from least to greatest RMS were 20 minutes, 24 hours, 0 minutes, 2 weeks, and 1 week. Post hoc analysis revealed that the time periods 20 minutes and 24 hours showed significantly better accuracy than two weeks and one week ($p \leq .05$) but not zero minutes, across all materials and methods of fabrication. The time period zero minutes showed significantly better accuracy ($p \leq .05$) than one week but not two weeks (Figure 5).

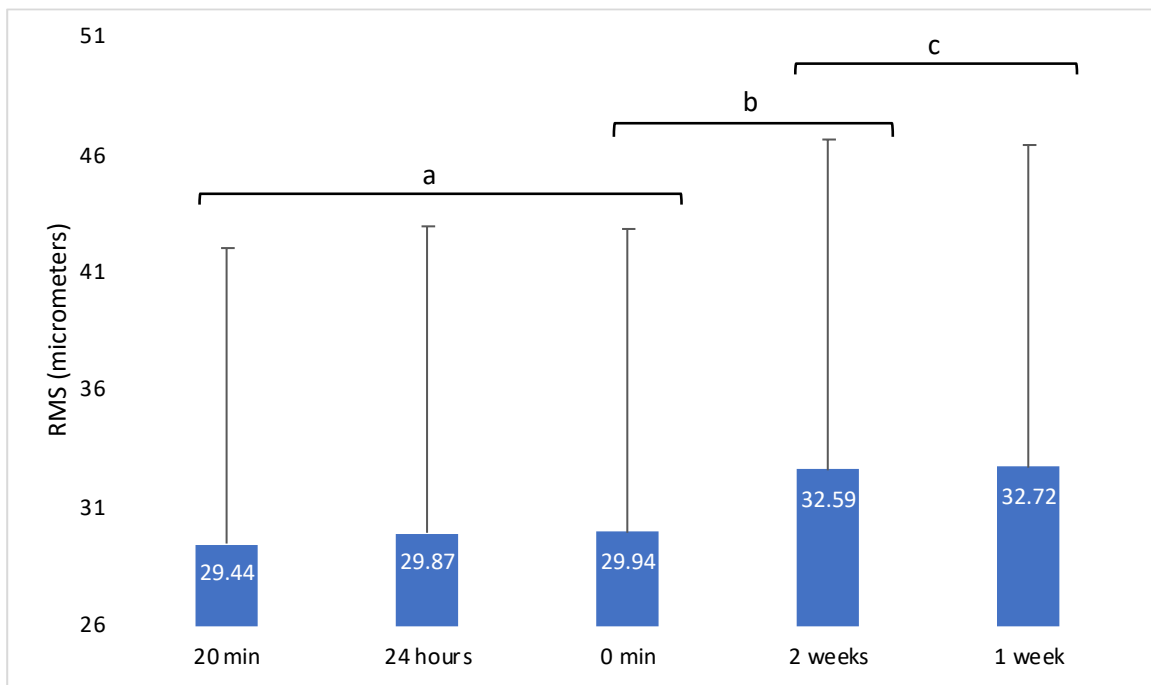


Figure 5. Effect of Time on Accuracy: Time periods 20 min, 24 hours, and 0 min, (a) were not significantly different; time periods 0 min and 2 weeks (b) were not significantly different; and time periods 2 weeks and 1 week (c) were not significantly different. Time periods 20 min and 24 hours had significantly better accuracy than 2 weeks and 1 week but not 0 min. Time period 0 min had significantly better accuracy than 1 week but not 2 weeks ($F = 5.303$, $p \leq .0005$).

The Effect of the Type of Material on Accuracy

Type of material significantly affected the accuracy of patterns fabricated ($F= 118.272$, $p \leq .0005$). The patterns fabricated in wax showed a significantly lower RMS than resin, indicating wax has significantly better accuracy (Figure 6).

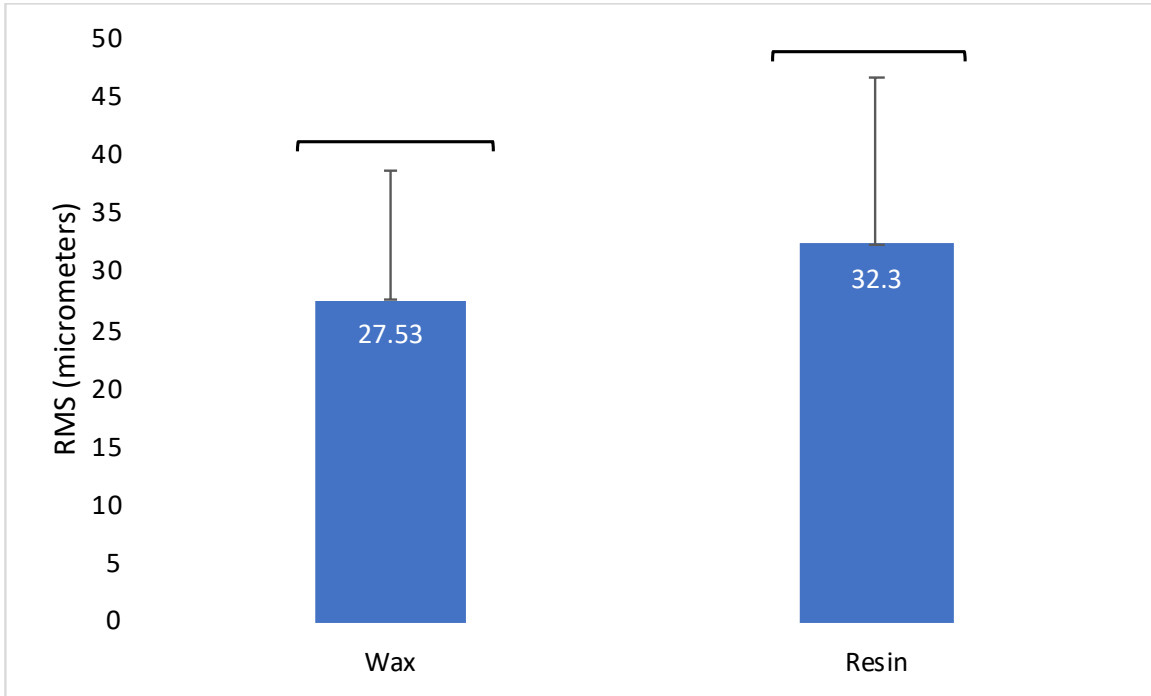


Figure 6. Effect of Type of Material on Accuracy: The patterns fabricated in wax showed significantly better accuracy than those of resin ($F=118.272$, $p \leq .0005$).

The Effect of the Method of Fabrication on Accuracy

The method of fabrication significantly affected the accuracy of the patterns ($F=1351.627$, $p \leq .0005$). The patterns fabricated by the subtractive manufacturing method showed a significantly lower RMS than the patterns fabricated by the additive manufacturing method (Figure 7).

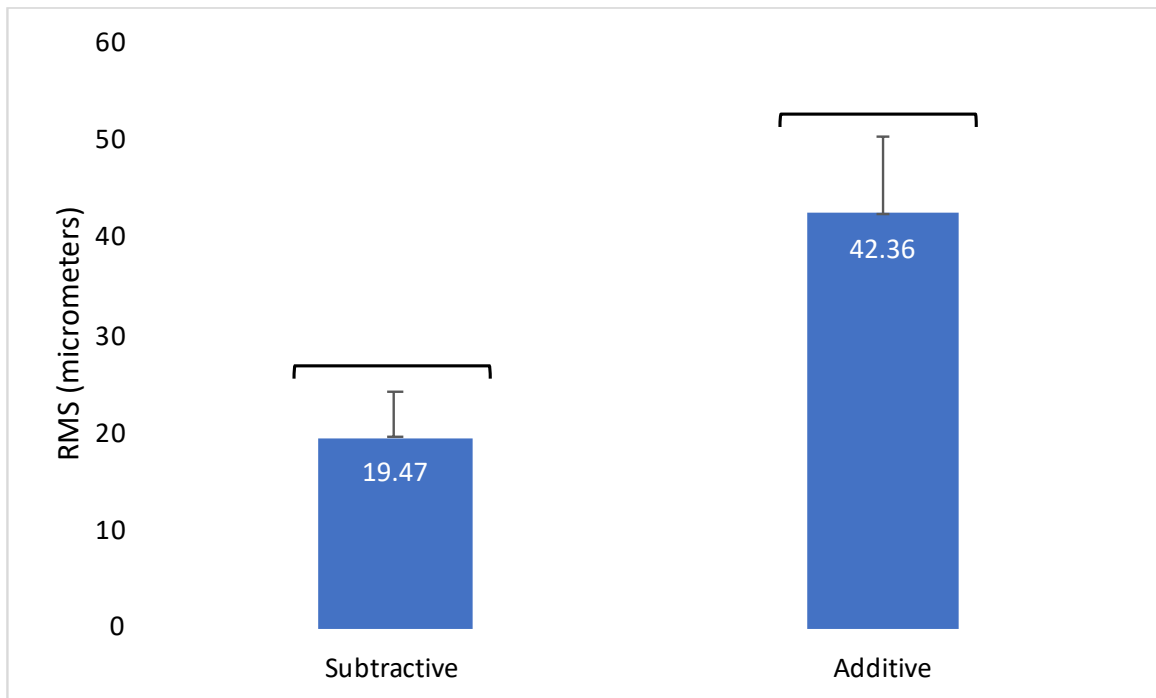


Figure 7. Effect of Method of Fabrication on Accuracy: Patterns fabricated by subtractive manufacturing showed significantly better accuracy than additive manufacturing ($F=1351.627$, $p \leq .0005$).

Interaction Between Time and Type of Material on Accuracy

The interaction between time and type of material significantly affected the accuracy of the patterns fabricated (Table 3, Figure 8). At all time periods, patterns fabricated in wax had significantly lower RMS than that of resin ($F = 3.630, p \leq .007$). There was an interaction between time (one week and two weeks) and type of material (wax and resin). The patterns fabricated in wax were more accurate at one week than at two weeks, while patterns fabricated in resin were more accurate at two weeks than at one week. There were smaller interactions between zero minutes, 20 minutes, and 24 hours.

Although patterns fabricated in wax had lower RMS values at each time period than those of resin, the changes in RMS between the time periods was greater with wax (Figure 8). For wax, zero minutes, 20 minutes, and 24 hours revealed similar RMS values. One week had higher RMS and two weeks had the highest RMS value. The accuracy of patterns fabricated with resin were similar for all time periods except for one week, which had a higher RMS value than the other time periods.

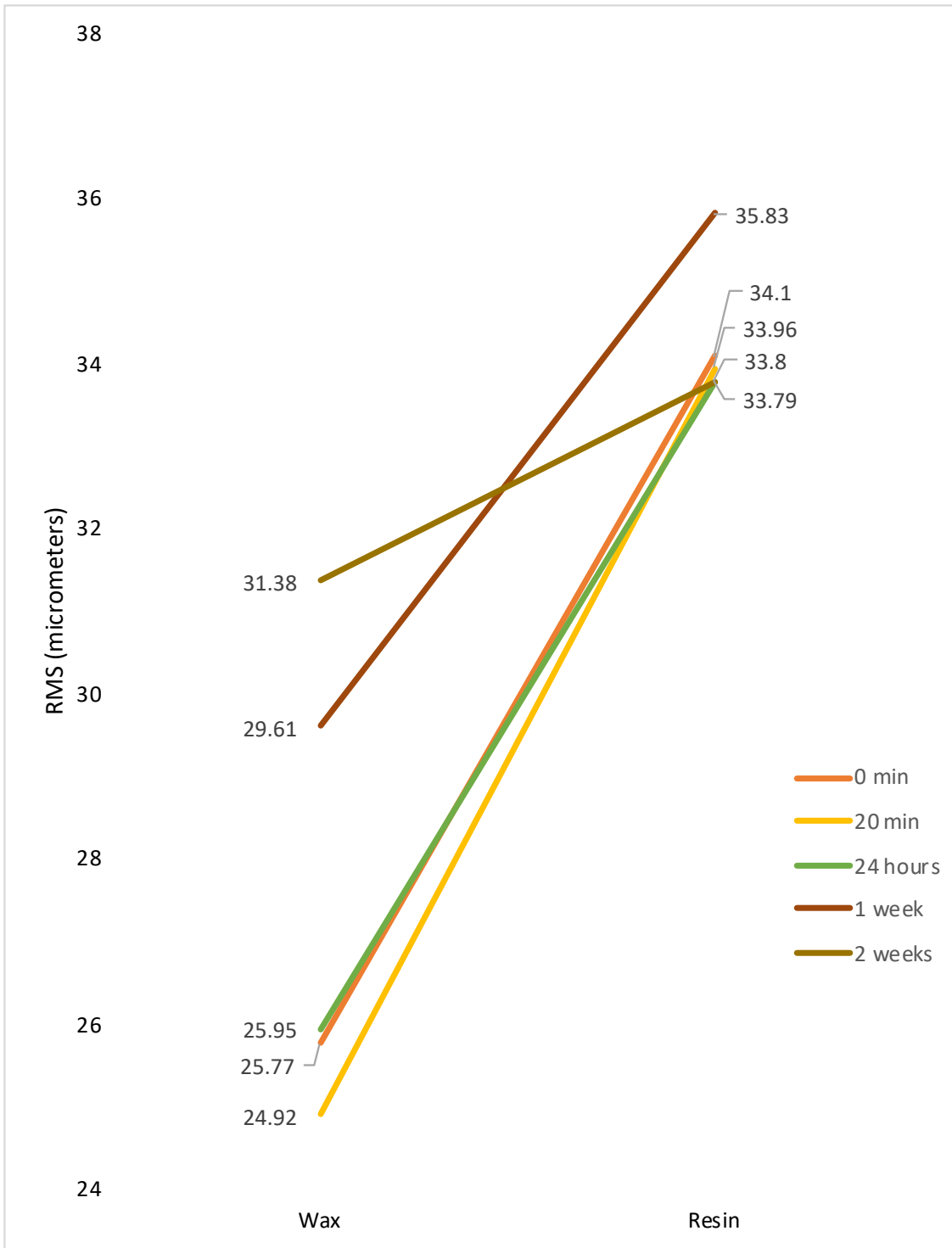


Figure 8. Interaction Between Time and Type of Material on Accuracy: At all time periods, patterns fabricated in wax showed significantly better accuracy than resin. The time periods that showed interaction were 1 week and 2 weeks ($F=3.630$, $p \leq .007$). Patterns fabricated in resin have less dimensional change between each of the time period.

Interaction Between Time and Method of Fabrication on Accuracy

The interaction of time and method of fabrication significantly affected the accuracy of patterns fabricated (Table 3, Figure 9). At all time periods, the patterns fabricated by subtractive manufacturing had significantly lower RMS than the patterns fabricated by additive manufacturing ($F=2.623$, $p \leq .036$). The changes in RMS between the time periods was also less with subtractive manufacturing (Figure 9).

In examining Figure 9, it can be seen that there is an interaction between two weeks and one week and also an interaction between 24 hours and 20 minutes, and 24 hours and zero minutes. However, these interactions were minimal. This is supported by the larger p value than all the other p values in Table 3 and also by the power analysis. The power analysis for time by method of fabrication resulted in a power of .729. A power value of $\geq .80$ indicates that there is a sufficient number of subjects in a statistical result.

Therefore, in this study a greater number of samples was needed to support the findings of the stated interaction.

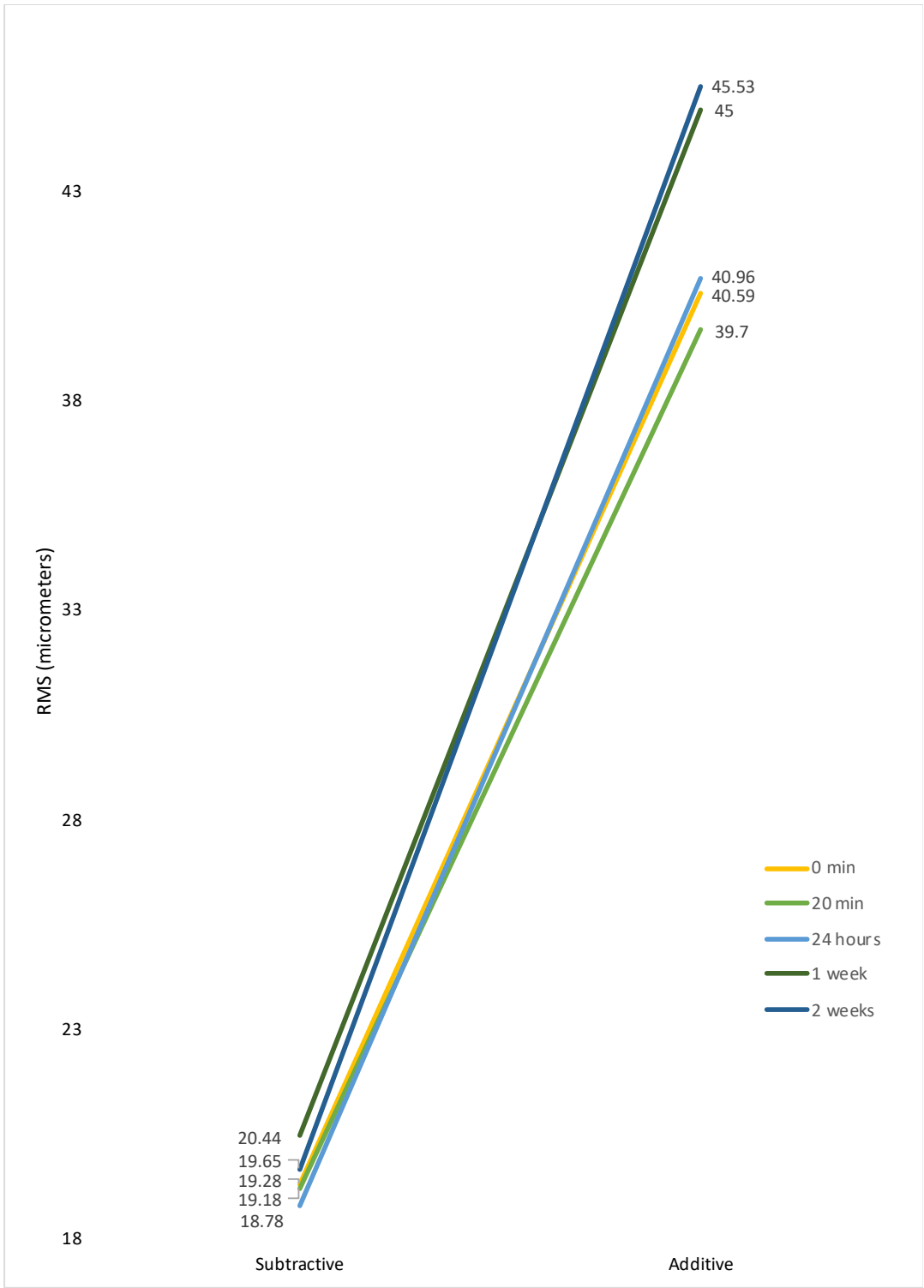


Figure 9. Interaction Between Time and Method of Fabrication on Accuracy: At all time periods, the patterns fabricated by subtractive manufacturing showed significantly better accuracy than patterns fabricated by additive manufacturing ($F=2.623, p \leq .036$). Patterns fabricated by subtractive manufacturing also have less dimensional changes between the time periods.

Interaction Between Type of Material and Method of Fabrication on Accuracy

The interaction between type of material and method of fabrication significantly affected the accuracy of patterns fabricated (Table 3, Figure 10). The subtractive method showed a lower RMS than the additive method no matter whether the patterns were fabricated in wax or resin ($F=43.139$, $p \leq .0005$). Although the results suggest that there is a sufficient number of subjects and a significant interaction between time and type of material, confirmed by the power value (1.000), the interaction is seen to occur outside the confines of the experimental variables.

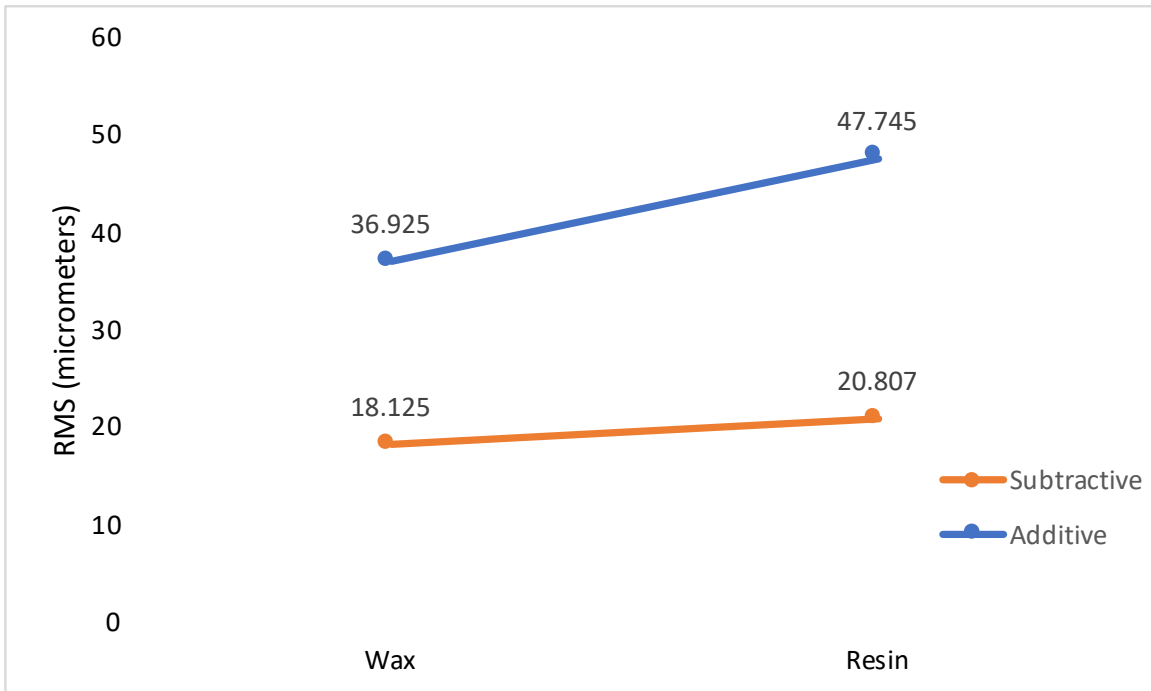


Figure 10. Interaction Between Type of Material and Method of Fabrication on Accuracy: The patterns fabricated by subtractive manufacturing had significantly better accuracy than additive manufacturing, regardless of the type of material used ($F=43.139, p \leq 0005$).

Interaction of Time, Type of Material, and Method of Fabrication on Accuracy

At all time periods, the patterns fabricated by subtractive manufacturing had better accuracy than those fabricated by additive manufacturing ($F=3.715$, $p \leq .006$). Looking at subtractive manufacturing alone and additive manufacturing alone, the patterns in wax had lower RMS than that of resin. When looking at the subtractive method, over all the time periods, there is little difference in whether wax or resin was used. However, within additive manufacturing the RMS values had a greater difference, in favor of wax, at the earlier time periods (zero minutes, 20 minutes, and 24 hours) than at one week and two weeks. The difference of the RMS values between the time periods is minimal for the wax patterns fabricated by subtractive manufacturing and resin patterns fabricated by subtractive and additive manufacturing.

Although the result suggests that there is a significant interaction, confirmed by the power value (.88), the two interactions (between resin and wax at both the subtractive and the additive methods) would actually occur outside the confines of the levels of the experimental variables.

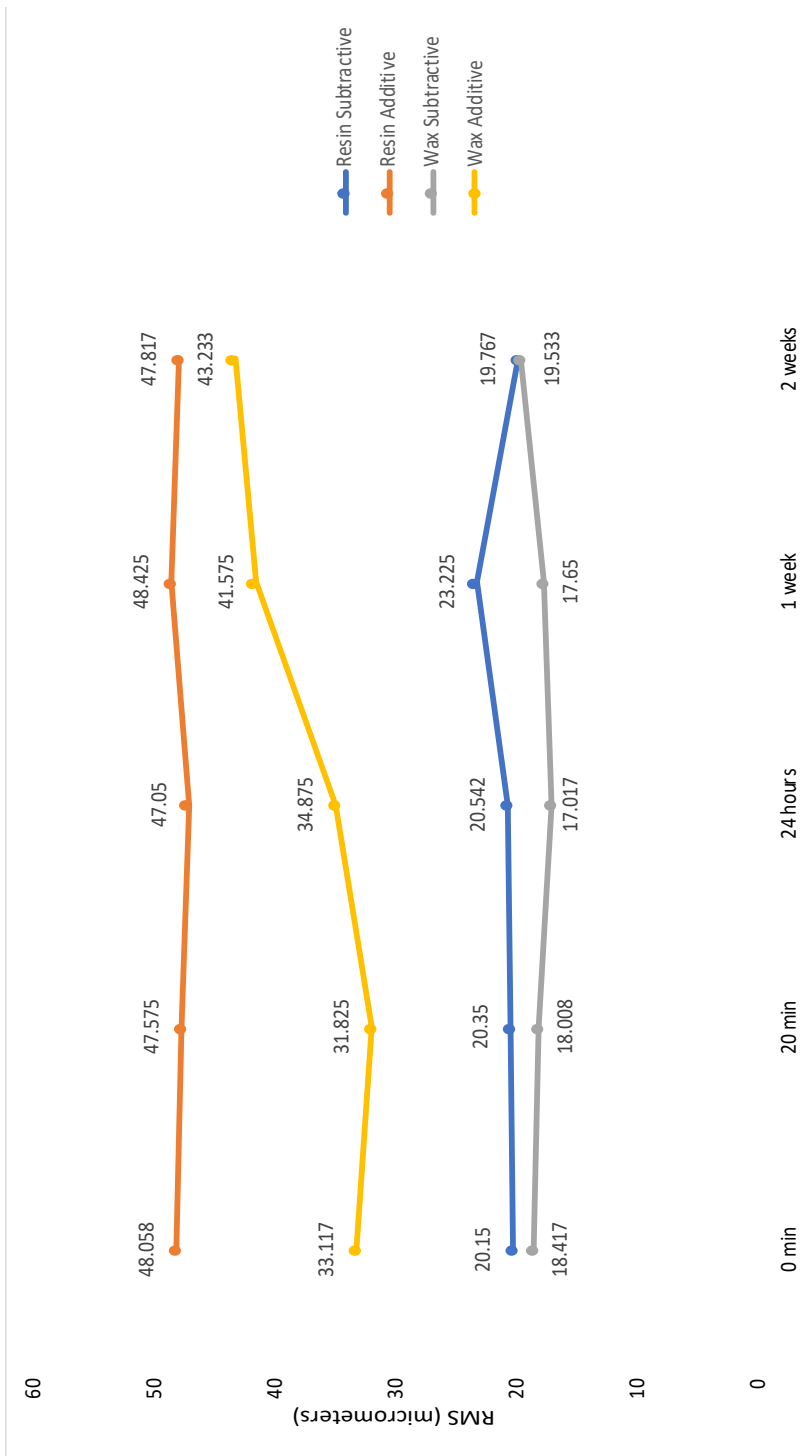


Figure 11. Time, Material, and Method of Fabrication on Dimensional Stability: Although time, type of material, and method of fabrication revealed a significant interaction, the interactions were observed outside the parameters of this study ($F=3.715, p \leq 0.006$). The subtractive manufacturing exhibited better accuracy than the additive manufacturing. For both fabrication methods, wax had superior accuracy than resin.

Discussion

In this study, the effect of time, type of material (resin and wax), and method of fabrication (additive and subtractive manufacturing) on the accuracy and dimensional stability of CAD/CAM patterns were evaluated. Based on the literature review completed, recent studies have evaluated CAD/CAM fabrication method or material type, but few have considered the interaction of the fabrication method and material type. Fewer studies have evaluated how time may affect the accuracy of CAD/CAM patterns. The results of this study demonstrated that time, material type, fabrication method, and all their interactions significantly affected accuracy of FDP patterns. As such, all the null hypotheses were rejected.

The accuracy of all patterns over time improved, then worsened, and then improved again. This was indicated by the decreasing and then increasing RMS values (Figure 5). When the two materials (resin and wax) are evaluated over time, the accuracy of both materials initially improved (Figure 8). The patterns fabricated in resin at zero minutes had an RMS of 34.1 micrometers and improved to 33.8 micrometers until the 24-hour period while wax at zero minutes had an RMS of 25.77 micrometers and improved to 24.92 micrometers until the 20-minute period (Figure 8). These improvement values are very small and are not likely to have clinical importance.

The resin pattern RMS was the worst with 35.83 micrometers at the 1-week period and then improved to 33.79 micrometers at the 2-week period. The wax pattern RMS gradually increased to 31.38 micrometers until the 2-week period. At the moment, there is no explanation for why the patterns showed initial improvement of dimensional stability. When examining previous research on both materials, a decrease in stability can

be expected for both materials.^{6, 10, 11, 12, 13, 14, 15} Although the results of this study indicate a significant effect, these dimensional changes are likely to be minimal and of no clinical importance.

When the type of material is considered, patterns fabricated in wax showed superior accuracy over resin (Figure 6). Regardless of the time period and manufacturing method, wax showed more accuracy over resin (Figure 11). The wax patterns from least to greatest RMS by time period was 20 minutes, 24 hours, zero minutes, one week, and two weeks. The resin patterns from least to greatest RMS by time period was two weeks, 24 hours, 20 minutes, zero minutes, and one week (Figure 8). Wax patterns showed superior accuracy over resin patterns, for both subtractive and additive manufacturing methods, by 2.7 micrometers and 10.8 micrometers, respectively (Figure 10). Wax patterns fabricated by additive manufacturing were less accurate than resin patterns fabricated by subtractive manufacturing (Figure 10). Although patterns fabricated in wax had significantly better accuracy than resin, patterns fabricated in subtractive manufacturing showed minimal differences between wax and resin patterns.

The results showing wax as superior to resin, in this study, are consistent with previous findings. A study by Homsy et al, comparing the fit of lithium disilicate inlays fabricated by CAD/CAM patterns, found that restorations fabricated by wax had less discrepancy.³⁹ However, Homsy et al indicated that the use of wet milling with their resin patterns could have resulted in undesired residue that also affected fit.³⁹ Past literature has shown that conventional casting waxes could shrink about 0.3-2.3%, while resins could shrink 4.5-7.5%.^{6, 17, 18}

When analyzing the data for total dimensional change, from initial fabrication to two weeks, patterns fabricated in wax produced greater dimensional change than that of resin. Regardless of the greater dimensional change, over time, wax still remained more accurate. The interaction of time and material type shown, in Figure 8, reveals that wax had better accuracy at all time periods but had greater change between time periods.

Studies by Rajagopal et al, Cahil et al, and Iglesias et al, that compared the dimensional stability of conventional inlay wax and resins patterns, found resin to have less marginal discrepancy than wax at 1 hour and 24 hours.^{12, 13, 14} This finding may be different from the present study because past studies only compared conventional wax and resins and only measured linearly. Also, unlike past studies that fabricated wax patterns by heating the wax, CAD/CAM methods consist of cutting away a block of wax or using a light source to cure the wax. Other considerations for the differing findings might be due to differences in storage conditions, variation of wax ingredients and resin ingredients, morphology and anatomy, and bulk of material.

In regard to method of fabrication, patterns fabricated by subtractive manufacturing were superior over the additive manufacturing method (Figure 7). The mean RMS of subtractive manufacturing was 19.5 micrometers while additive manufacture was 42.4 micrometers.

Additive manufacturing, specifically SLA the additive manufacturing used in this study, is known for shrinkage during photopolymerization.⁴⁰ Although it may depend on the various printers available, distortion and shrinkage can be a downside of SLA.²⁵ A study by Karalekas and Aggelopoulos sought to evaluate the amount of shrinkage present

during polymerization of two resin plates fabricated by stereolithography.⁴¹ They found that shrinkage was present during the post-cure. Their findings were illustrated by the “formation of circular fringes” or “elliptical fringes”, that cause the laminates to deflect during the post-cure.⁴¹ In our study, the patterns fabricated in resin by additive manufacturing were post-cured and this may have contributed to the dimensional changes observed. At every time period, the mean RMS was higher for patterns fabricated in resin by additive manufacturing than the mean RMS of all other samples, indicating less accuracy. However, patterns fabricated in resin by additive manufacturing had minimal dimensional change between the time periods (Figure 11). The post-cure of the resin may be a factor in causing distortion and shrinkage, resulting in less accuracy than wax. However, when the additive resin is post-cured, full polymerization could help prevent dimensional changes over time and can be a benefitting quality over the additive wax.

One study by Kim and another by Yau et al compared the accuracy of subtractive and additive manufacturing of dental models.^{42, 43} Both studies found that the subtractive method was more accurate.^{42, 43} A study by Braian et al, that evaluated production of various metal objects, found that both additive and subtractive manufacturing could not produce a product with a perfect match to the STL file.⁴⁴ Of the two methods evaluated in Braian et al’s study, subtractive manufacturing was superior than additive manufacturing both in accuracy and precision.⁴⁴ Although the three studies agree with the present study, they are not true comparisons since they do not produce or evaluate FDP patterns.

The present study may have shown that subtractive manufacturing had better accuracy, other studies have shown that additive manufacturing has greater accuracy.^{24, 27, 45} Many of the studies that showed additive manufacturing to be superior used a printer that

utilized a different type of additive manufacturing method or a printer that prints in finer layers with finer resolution than used in this study. In addition, because additive manufacturing can better produce small openings (i.e. cusp points, edges, grooves and fissures), it is possible that the other studies might have shown better accuracy with additive manufacturing.⁴⁵ Keeping this limitation of subtractive manufacturing in mind, the scanned preparations of the typodont teeth in this study were made rounded, smooth, and avoided edges and peaks.

Patterns fabricated in wax by additive manufacturing (Castable Wax) had the second worst dimensional stability at all time periods (Figure 11). It is possible that due to photopolymerization during the initial cure, some distortion takes place. However, the additively manufactured wax patterns did not receive a post cure and this may be the reason why it had better accuracy than the additively manufactured resin patterns.

When comparing the change in RMS between time periods, patterns fabricated in wax by additive manufacturing had the most dimensional change over the periods tested. Part of this could be because a post-cure is not used with Castable Wax. This might mean that the material is not fully polymerized and as time passes, the material may be more susceptible to dimensional change.

A major factor to consider when analyzing the manufacturing specification is the manufacture resolution. The subtractive manufacturing unit in this study did not appear to have a resolution reported in the manual or other specifications. We attempted to contact the manufacturer for these specifications but received no response. The printer used for additive manufacturing in this study was reported to print at the lowest XY-resolution (or

horizontal resolution) of 150 microns.³² The Z-resolution (or vertical resolution) can range from 25-300 microns, but a layer thickness of 50 microns was selected for this study.³² The combination of the XY-resolution and Z-resolution can help produce the most accurate and detailed object.³² If the milling resolution of the subtractive manufacturing unit in this study was reported and found to be lower than the additive manufacturing unit, it is possible that this may explain the superior accuracy of subtractive manufacturing over additive manufacturing. However, the lack of information does not allow this. When considering manufacturing resolution, the time it takes to manufacture an object must also be taken into consideration. Therefore, not all objects can be fabricated in the lowest resolution.

Although statistical analysis of this study found significant interactions between the independent variables (time, type of material, and method of fabrication), none of these interactions appear to be clinically important. Differences are likely due the very large N of 720 yields significant results. When evaluating Figures 5 thru 8, only Figure 8 shows obvious crossing interactions between weeks two and one. However, in Figure 8, the differences between the obvious crossing time periods only differ by 6-7micrometers and may not have a clinical impact. The remaining time periods of Figure 8 and the interactions in Figure 9 are minimal, and the differences between the crossing are unlikely to have a clinical impact. Figure 10 and Figure 11 would only show interactions beyond the confines of this study.

All patterns had a deviation from the reference that fell within a range of 11 micrometers to 57 micrometers at all measured periods (Appendix 1), which is likely to result in distortions of the margin and internal fit. The American Dental Association (ADA)

provides a range of 25-40 micrometers for a maximum cement thickness.⁴⁶ For margin opening, several early reports have reported an acceptable marginal opening should be less than 40-50 micrometers.^{47, 48, 49} Others have revealed that prosthodontists and predoctoral students found acceptable marginal gaps ranging from 66 micrometers up to 455 micrometers.⁵⁰ A routinely cited study by McLean and von Fraunhofer revealed that a marginal gap of up to 80 micrometers was not detectable radiographically and a 200 micrometer gap was not detectable with a probe of 80 micrometers.⁵¹ In their five year study, McLean and von Fraunhofer concluded that the maximum opening of a 120 micrometer marginal gap was clinically acceptable.⁵¹

With such a wide range for acceptable crown margins gaps, it is difficult to say what is clinically acceptable. The results of this study revealed that the pattern with the largest deviation was 57 micrometers, which would fall well within the range of acceptable error yet resulting in clinically acceptable fit as discussed above. However, it is important to note that the measurement of this study was not a linear measurement at the crown margin, but a sum of all deviations on the intaglio surface of the pattern including the margin. Additional research specifically quantifying internal fit and marginal opening of additive and subtractive manufactured prostheses is necessary.

Another area of concern related to FDP dimensional stability is the internal fit and cement space. Distortion that increases the cement space or the gap between the axial walls of the prep and the pattern could affect retention of the pattern. Jorgenson and Esbensen found that a decrease of retention was noted when cement thickness was 140 micrometers or greater.⁵² In this study, the pattern was designed with a total cement gap of 110 micrometers per default of 3-Shapes Dental Design software (see Figure 1).

Although deviations can occur as a shrinkage or expansion, it is possible that the patterns can lose retention if the deviation occurred as an expansion of 57 micrometers. If there is concern noted with loss of retention due to a large cement gap, the cement gap space can and should be modified on the design software as needed. Shrinkage and expansion were not evaluated so it is not possible to ascertain whether the deviation or distortion would create a larger gap.

This study did not evaluate linear measurements but an overall measurement of the entire intaglio surface, including the margin, of the FDP pattern using the Geomagic software. The marginal gap was not measured. The fit of the patterns on a die was not measured. Examining the dimensional stability of the patterns before investing and casting allows for an evaluation of the pattern material and fabrication method. The dentist or dental technician is equipped with more information when choosing the type of material or manufacturing method they work with. Although, more information on the relationship of the pattern material to investment process and final casting may be needed.

Limitations

A major limitation to this study is that there was no comparison to conventional hand wax patterns. The method of comparing CAD/CAM patterns to its reference and hand-wax patterns to its reference are not equivalent and so this was not performed. The reference for the CAD/CAM pattern would be a digital design file obtained from the design software while the reference for the hand-wax pattern would be a scan of the wax-up, which would cause inaccuracies. However, past studies that have compared linear measurements at the margin have shown that CAD/CAM patterns showed superior dimensional stability to conventional hand-wax patterns.^{6,10,19,30,}

Another limitation of the study is that it did not evaluate the direction of the deviation or distortion. Instead, it evaluated an overall dimensional change (RMS value). It may be critical to know in which direction, positive or negative, the surfaces and dimensional change occurred as the deviation or distortion may affect the fit and occlusion of the FDP.

Further Research

Future studies could investigate the linear measurement of CAD/CAM patterns and the direction of the dimensional changes measured. This can be done by evaluating the patterns on a dye. Future studies could also look at the effect of setting and thermal expansion on the CAD/CAM patterns that can occur during the investment and casting process.

Conclusions

The dimensional stability of CAD/CAM patterns is significantly affected by time, type of material, method of fabrication, and their interactions. Although time had a significant effect on the dimensional stability of patterns, the dimensional change over time might not have a clinical importance. Even though there is no clinical impact, it is recommended that patterns be invested as soon as possible. However, given a situation that the pattern is invested at a later time (up to 2 weeks after fabrication), fabricating a well-fitting final restoration might still be possible.

CAD/CAM patterns fabricated in wax material had significantly better accuracy than resin, but the clinical impact may be minimal. CAD/CAM patterns fabricated by subtractive manufacturing had significantly better accuracy than that of additive manufacturing, but the clinical impact may be minimal. In regards to the material type and fabrication methods, the clinician/technician should choose the material type and fabrication method that they are most familiar with and able to produce the most accurate final restoration.

Appendix

Appendix 1: Raw data measurements RMS (in micrometers)

Castable Resin	0 min	20 min	24 hours	1 week	2 weeks	Avg
1	48.8	48.8	46.8	49.2	48.3	48.38
2	55	55.8	51.5	49.2	57	53.7
3	55.1	51.6	56.2	55.4	52	54.06
4	41.4	43.2	44.6	49	45.4	44.72
5	46.1	43.8	45.5	47.2	47.7	46.06
6	52	47.6	51.9	52.2	50.4	50.82
7	48.2	46	47.1	46.5	47.5	47.06
8	53.4	54.8	52.1	50.2	51.9	52.48
9	51.2	51.6	51.5	52.8	53.3	52.08
10	39.1	40.4	37.5	42.5	38.3	39.56
11	41.2	41.8	37.3	40.9	39	40.04
12	45.2	45.5	42.6	46	43	44.46
Avg	48.058	47.575	47.05	48.425	47.817	47.785

Castable Wax	0min	20 min	24 hours	1 week	2 weeks	Avg
1	28.4	28.7	30.3	38.6	42.6	33.72
2	23.7	23.4	24.4	29.6	35.1	27.24
3	31.5	30.7	35	42.5	46.7	37.28
4	31.9	30.3	39.7	44.6	45.7	38.44
5	31.8	32.3	31.4	38.2	36.2	33.98
6	31.1	30.6	35.6	41.1	41.4	35.96
7	38	35.2	36.5	43.7	42.8	39.24
8	39.6	38.5	38.2	43.5	42.4	40.44
9	32	30	32.4	40.8	42.5	35.54
10	34.1	33.4	32.8	39.1	41.2	36.12
11	39.6	36.9	43.5	51.7	53.3	45
12	35.7	31.9	38.7	45.5	48.9	40.14
Avg	33.117	31.825	34.875	41.575	43.23	36.925

Milled PMMA	0 min	20 min	24 hours	1 week	2 weeks	Avg
1	18.6	18.5	18.2	27.9	20.3	20.7
2	19.6	16.8	17.3	20	16.7	18.08
3	18.3	16.8	16.6	23.9	16.7	18.46
4	19.1	19.4	17.4	20.5	16.9	18.66
5	21.3	23.5	22.2	24.2	18.7	21.98
6	17.3	16.1	15.1	16.1	14	15.72
7	17.7	19.4	17.9	17	20.9	18.58
8	19.3	21.4	22.6	16.2	18.4	19.58
9	16	17.9	21	18.1	20.8	18.76
10	28.5	24.5	26.3	33.5	26	27.76
11	22.6	25.5	25.6	29.6	23.3	25.32
12	23.5	24.4	26.3	31.7	24.5	26.08
Avg	20.15	20.35	20.542	23.225	19.767	20.807

Milled Wax	0 min	20 min	24 hours	1 week	2 weeks	Avg
1	15	14.2	13.5	14.2	14.2	14.22
2	14.1	14	13.2	14.5	15.2	14.2
3	13.9	13.4	14.7	14.9	19	15.18
4	24.6	24.6	23.2	22.9	23.5	23.76
5	23.7	23.7	22.1	24.9	23.8	23.64
6	22.3	22.2	20	20.7	23.6	21.76
7	22.3	21.1	21.5	20.9	26.9	22.54
8	27.1	26.3	24.7	22	26.6	25.34
9	14.1	14.5	12.2	15.2	15.3	14.26
10	13.3	14.2	11.4	14	15.1	13.6
11	13.9	13.2	13.5	13.6	14.7	13.78
12	16.7	14.7	14.2	14	16.5	15.22
Avg	18.416	18.008	17.017	17.65	19.533	18.125

Appendix 2: Pilot Study RMS Results (in micrometers)

Castable Resin	0 min	20 min	24 hours	1 week	2 weeks
1	48.8	48.8	46.8	49.3	48.3
2	55	55.8	51.5	49.2	57
3	55.1	51.6	56.2	55.4	52
avg	52.967	52.067	51.5	51.3	52.433

Castable Wax	0 min	20 min	24 hours	1 week	2 weeks
1	28.4	28.7	30.3	38.6	42.6
2	23.7	23.4	24.4	29.6	35.1
3	31.5	30.7	35	42.5	46.7
avg	27.867	27.6	29.9	36.9	41.467

Vericore PMMA	0 min	20 min	24 hours	1 week	2 weeks
1	18.6	18.5	18.2	27.9	20.3
2	19.6	16.8	17.3	20	16.7
3	18.3	16.8	16.6	23.9	16.7
avg	18.833	17.367	17.367	23.933	17.9

Vericore Wax	0 min	20 min	24 hours	1 week	2 weeks
1	15	14.2	13.5	14.2	14.2
2	14.1	14	13.2	14.5	15.2
3	13.9	13.4	14.7	14.9	19
avg	14.333	13.867	13.8	14.533	16.133

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