Physical and Optical Properties of Provisional Crown and Bridge Materials Fabricated Using CAD/CAM Milling or 3D Printing Technology

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PHYSICAL AND OPTICAL PROPERTIES OF PROVISIONAL CROWN AND BRIDGE MATERIALS FABRICATED USING CAD/CAM MILLING OR 3D PRINTING TECHNOLOGY.

NIRANJAN JOSHI, B.D.S., M.D.S.

A Thesis presented to the Faculty of the College of Dental Medicine of

Nova Southeastern University in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

July 2019

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By

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TITLE OF SUBMISSION: Physical and optical properties of provisional crown and bridge materials fabricated using CAD/CAM milling or 3D printing technology

DATE SUBMITTED: July 2019

I certify that I am the sole author of this thesis, and that any assistance I received in its preparation has been fully acknowledged and disclosed in the thesis. I have cited any sources from which I used ideas, data, or words, and labeled as quotations any directly quoted phrases or passages, as well as providing proper documentation and citations. This thesis was prepared by me, specifically for the M.S. degree and for this assignment.

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Dedication

I would like to dedicate this thesis to my parents Dr. Ratnakar Joshi and Chhaya Joshi, to my wife Dr. Vedavati Joshi, my daughter Eva and all my close friends who stood by me during these three years.

Acknowledgements

- First, I would like to thank my mentor Dr. Jeffrey Thompson who helped me and guided me throughout the study. I would also like to thank him for being patient with my project and helping me navigate this journey.
- I would like to express my gratitude to Dr. Jack Piermatti for being a great teacher, mentor and for his guidance and his suggestions throughout the study.
- I am grateful to Dr. Thomas Balshi for his valuable suggestions and mentoring this study.
- I am thankful to Dr. Leila Ahmadian for her extremely valuable and helpful suggestions.
- I am thankful to Mr. Anthony Smithswick and Mr. Matt Winstead from Oral Arts Dental Laboratory, for their generous support in providing samples.
- I am grateful to Dr. Max Nahon for always supporting me in this study.
- I am thankful to Tariq Rehman for his support and suggestions during the study.
- I would also like to thank Dr. Patrick Hardigan for providing with the statistical analysis.
- I appreciate the help from Ria Achong-Bowe for her help in the Bioscience Research Center. Without her help this study wouldn’t have been possible.

ABSTRACT

PHYSICAL AND OPTICAL PROPERTIES OF PROVISIONAL CROWN AND BRIDGE MATERIALS FABRICATED USING CAD/CAM MILLING OR 3D PRINTING TECHNOLOGY.

DEGREE DATE: JULY 2019

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Objective:

This study compared the physical and optical properties of provisional crown and bridge materials fabricated using CAD/CAM or 3D printing technology.

Aim:

To compare the biaxial flexural strength, microhardness, translucency parameter and gloss of provisional resin discs fabricated by milling PMMA blocks, versus two different resins printed using 3D printers.

Hypothesis:

There is no difference in the flexural strength, hardness, translucency and gloss of provisional resins fabricated by different digital technologies.

Materials and methods:

90-disc shaped specimens for provisional resins were fabricated using a common digital file. These samples were equally distributed in three groups of 30 each. Group I samples were fabricated by milling specimens from a polymethyl methacrylate (PMMA). Group II samples were fabricated by printing urethane methacrylate resin using a 3D DLP printer. Group III samples were fabricated by printing acrylic ester resin using a 3D SLA printer. All samples were tested for biaxial flexural strength, translucency parameter, microhardness and gloss.

Results

A one-way ANOVA with Tukey HSD pair-wise comparisons was employed to analyze the data and answer the research questions. The mean values for biaxial flexural strength for milled polymethyl methacrylate (PMMA), urethane methacrylate resin and acrylic ester resin were 136.9 MPa, 101.6 MPa and 98.4 MPa respectively. The mean hardness values for the groups in the same order were 28.5, 9.7 and 14.8 respectively. The mean translucency parameter values for the groups in the same order were 3.8, 6.3 and 4.4 respectively. The mean gloss values for the groups in the same order were 3.9, 28.8 and 1.7 respectively. There was a statistically significant difference amongst the groups for all parameters tested.

Conclusion

The results of this study indicate that milled PMMA has superior flexural strength and hardness compared to 3D printed resins. Urethane methacrylate resin showed significantly better translucency and gloss when compared to milled PMMA or acrylic ester resin. Each approach to creating provisional restorations displayed advantages and disadvantages when comparing characteristics of clinical interest.

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CHAPTER 1

INTRODUCTION

1.1 Provisional restorations

Provisional restorations are an integral part of fixed prosthodontics as they provide protection and function to the prepared teeth while the definitive restorations are fabricated. The ability to easily modify these provisional restorations provides diagnostic value. More complex rehabilitations need provisional restorations to provide a blue print for fabricating definitive restorations. Esthetics, contours and comfort are all assessed in provisional restorations and modified accordingly.[1,2]

Provisional restorations mimic definitive restorations in all aspects of form, function and appearance. The major difference that separates the two is durability. While definitive restorations are designed to last a very long time, provisional restorations need to be functional for shorter durations. However, these shorter durations vary according to treatment timelines, complexity of any specific case, and healing time of any surgeries performed during treatment. Certain requirements for good provisional restorations have been suggested. These include pulpal protection, positional stability, occlusal function, ease of cleaning, non-impinging margins, strength, retention and esthetics.[1]

1.2 Types of provisional restorations

Provisional restorations can be classified as prefabricated or custom-made ones. Prefabricated restorations are more commonly prefabricated tooth colored polycarbonate crowns with the ability to be relined for fit. These come in multiple shapes, shades and forms and the clinician can select one which fits best for the given situation. Although they provide excellent esthetics, they are limited in use for single crowns.[1]

More complex restorations need customized provisional restorations. Custom made provisional restorations can be made by multiple techniques with different materials. These choices increase treatment versatility.

1.3 Techniques for fabricating provisional restorations.

Custom made provisional restorations can either be fabricated directly or indirectly. In the direct technique acrylic resin is mixed with a monomer to make a doughy mix which is placed directly on the tooth preparation. A silicone/ alginate matrix from a wax up or a free form block can be used to deliver the material to the tooth preparation. After it is set, it is removed from the mouth, contoured and shaped.[1,2] Polymethyl methacrylate (PMMA) as a material has a setting reaction which is highly exothermic. The direct method is thereby extremely technique sensitive with temperature regulation and cooling being vital during the process. There is also an increased amount of direct contact of the free monomer with the freshly cut dentin and surrounding soft tissues. Chances of the acrylic getting stuck interproximally is also significantly higher with this technique.[1]

The indirect technique involves fabricating the provisional from a model of the prepared teeth. Since it needs to be done with patient seated at the operatory, it is a less common method of fabricating provisional restorations.

More often an indirect-direct technique is used to fabricate provisional restorations. A shell of acrylic is pre-fabricated from a mock preparation of the teeth and a wax up. This shell is hollowed out and relined using acrylic directly on the preparation. This minimizes the amount of acrylic in direct contact with the teeth. Since the reline material occupies minimal space, the heat from the exothermic reaction can be managed in a more controlled way.[2]

Since the advent of CAD/CAM in dentistry, provisional restorations can now be fabricated by milling of high-density acrylic billets.[3] The CAD software allows for superimposition of the virtual wax up and the tooth preparation. A provisional restoration can then be designed and milled from the generated CAD file.[3] More recently, the same CAD file can also be used to 3D print provisional restorations.[4]

1.4 Provisional restorative materials.

Different materials have been used to fabricate provisional restorations. Acrylic resins have been by far the most commonly used material. Acrylic resins are relatively inexpensive and easy to use. Different acrylic materials available include:[2]

1. Poly methyl methacrylate: Offer good strength, polishability and durability, but also exhibits high polymerization shrinkage, high free monomer content and a highly exothermic reaction.
2. Poly ethyl methacrylate: Has minimal exothermic reaction and shrinkage, but tends to have lower fracture toughness and durability.
3. Poly vinylethyl methacrylate: Has good polishability and stain resistance, but has poor fracture toughness and esthetics.
4. Bisacryl composites: Have good strength, low exothermic heat generation, but are limited by shade selection, polishability and brittle nature.
5. Visible light cure urethane dimethacrylates: Have a controllable working time, good strength and abrasion resistance, but are expensive, and have poor marginal fit and are brittle.

Use of metal to reinforce acrylics has substantially increased their longevity.[5] This requires additional procedures to fabricate and incorporate metal within a provisional restoration, increasing fabrication time and cost of a restoration. Addition of metal also increases the overall bulk of the restoration, reducing comfort, and can also change the color, altering esthetics.

1.5 CAD CAM applications

Use of CAD/CAM milling technology has improved the physical properties of provisional restorations.[6,7] Acrylic in the form of PMMA is condensed under heat and pressure to fabricate highly dense “billets”.[8] These billets are then used to mill different structures based on a CAD file.[6] Although the strength of these dense acrylics is increased, milling from a “block” of material remains a subtractive process. It involves an increased waste of material as well as the increased cost of a milling unit and cutting burs.[9] The shapes fabricated by these milling units are limited by the size of the puck and by the burs used. Milling units are often limited by their axes of rotation, further reducing the range of shapes that can be created.

1.5.1 Advantages:

a. Material properties can be predictably controlled thus producing denser structures.
b. Precision and accuracy in reproducing shapes.
c. Saves significant time and manual labor.
d. Potentially any material can be used.

1.5.2 Dis-advantages:

a. Subtractive process which creates a lot of waste.
b. Limited in complexity of shapes produced by the axis of the mill and bur head size.
c. Increased cost of equipment and maintenance.
d. Difficult to have it available in-office.

1.6. 3D printing applications

More recently, the use of 3D printing has emerged as another option to fabricate provisional restorations.[10] 3D printing involves curing of liquid resin with light or lasers in an incremental fashion to produce complex structures. 3D printing can be achieved by fused deposition modelling (FDM), where a solid resin filament is passed through a nozzle to be ejected as fine lines, or by a laser stereolithographic apparatus (SLA), where a laser beam cures liquid resin in incremental lines.[9,11] SLA printers are more commonly used as they produce structures with resolutions as low as 25 microns as opposed to FDM printers, which are limited to approximately 100 microns. Resin structures fabricated by 3D printing use as much as 40% less material when compared to milling technologies.[12]

Structures printed with an SLA technique need to be post processed to achieve the final product. This post-processing includes washing the structure in isopropyl alcohol and then curing in UV light for up to three hours.[11] 3D printers range from inexpensive ones designed for in-house use to higher-end laboratory models.

1.6.1 Advantages

a. Complex geometrical structures can be produced.
b. Minimizes waste as uncured resin can be re-used.
c. Ability to have in-office printers.

1.6.2 Dis-advantages

a. Interfaces between printed layers could be weak links.
b. Difficult to produce dense structures.

c. Limited by the material choices which can be cured by light/laser.

d. May take significant time to print large and complex structures.

1.7 Strength of provisional materials

1.7.1 Biaxial flexural strength

Even though provisional restorative materials are less durable than definitive ones, they still do need to possess adequate mechanical properties to withstand the forces of mastication.[13] These restorations tend to have thicknesses in the range of 0.5 mm to 2 mm. Materials with adequate bulk will naturally have an increased strength, but it is critical to know the strength of these materials in thinner sections. Earlier studies have shown that biaxial flexural strength analysis shows more differences amongst materials tested and has strength value estimates closer to those obtained by finite element analysis (FEA).[14-16]

1.7.2 Microhardness

Microhardness is another important parameter to consider with provisional restorative materials. Hardness of a material is dependent upon other physical properties of strength, elastic limit, abrasion resistance, ductility and malleability.[14-17] Hardness of a material also influences wear resistance, which is a critical parameter to retain the shape of a provisional restoration throughout the duration of its use.[7,14,18]

1.8 Optical properties of dental materials

Provisional restorations should have optical properties very similar to the final restorations. This allows the clinician and the patient to visualize the esthetics of final restorations prior to being fabricated.

1.8.1 Translucency

Translucency of these acrylic materials gives vitality and life-like appearance to a provisional restoration. To achieve the best esthetics, a restorative material should interact with light in a manner similar to a natural tooth.[19] The translucency parameter of 1 mm sections of human dentin and enamel have been reported to be 16.4 and 18.7.[20] These values should define the translucency target for potential provisional restorative materials.

1.8.2 Gloss

Gloss measures the reflectivity of a surface. Gloss unit (GU) values range from 0-100 with less than 10 GU indicating low gloss and 70 GU or higher considered high gloss.[21] Previous studies measured enamel gloss to be around 6 GU[22] and our study aimed to evaluate gloss values of provisional acrylic resins.

1.9 Purpose, Specific Aims and Hypothesis

1.9.1 Purpose:

The overall purpose of this study was to compare physical and optical properties of provisional crown and bridge materials fabricated using CAD/CAM or 3D printing technology.

1.9.2 Specific aims and hypothesis

Specific aim 1: To compare the biaxial flexural strength of provisional resin discs fabricated by milling PMMA blocks, versus 2 different resins printed using 3D printers.

Hypothesis: There is no difference in the biaxial flexural strength values of provisional resins fabricated by different digital technologies.

Specific aim 2: To compare the microhardness of provisional resin discs fabricated by milling PMMA blocks, versus 2 different resins printed using 3D printers.

Hypothesis: There is no difference in the microhardness values of provisional resins fabricated by different digital technologies.

Specific aim 3: To compare the translucency parameter of provisional resin discs fabricated by milling PMMA blocks, versus 2 different resins printed using 3D printers.

Hypothesis: There is no difference in the translucency parameter (TP) of provisional resins fabricated by different digital technologies.

Specific aim 4: To compare gloss of provisional resin discs fabricated by milling PMMA blocks, versus 2 different resins printed using 3D printers.

Hypothesis: There is no difference in the gloss of provisional resins fabricated by different digital technologies.

Chapter 2

Materials and Methods

Approach

2.1 Specimen fabrication

Ninety samples were fabricated by 3 different techniques to obtain 30 disc shaped specimens (9.4 mm x 1.0 mm) per group. These specimens were used to measure the following physical and optical properties: Biaxial flexural strength, Vickers microhardness, translucency parameter and surface gloss. An initial stl (standard tessellation language) file was created using a free software called Meshmixer (Autodesk Inc, California, USA). This computer-generated CAD file is a common file that can be used for milling or 3D printing (Figure 1).

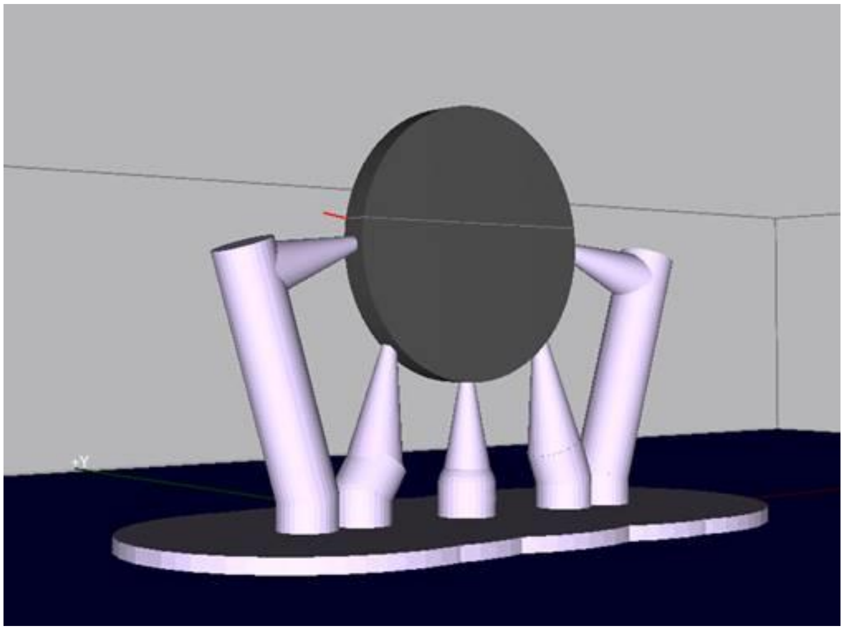

Figure 1. STL file common for milling or printing. (Meshmixer, Autodesk Inc, California, USA).

The specimens were grouped and fabricated as follows:

Group I:

Disc shaped specimens were printed using a 3D printer and a resin. Liquid acrylic resin containing urethane methacrylate and an acrylic monomer was obtained (Dentca™ Inc, California, USA) (Shade A1). The 3D printer used was a Cara 4.0 digital light processing (DLP) printer **(**Kulzer GmbH, Indiana, USA) (Figure 2) and the specimens were printed in increments of 50µm. After printing, the specimens were soaked in an alcohol bath for 15 min. The specimens were then completely submerged in a glycerol container and the container was placed for 30 min in a blue ultra violet light curing system with wavelength of 410nm (Dymax ECE 5000, Dymax corporation, Torrington, CT, USA) (Figure 3). Post-processed specimens were snapped off the build platform and sprue areas were smoothed with a rubber wheel.

Figure 2. Cara 4.0 digital light processing (DLP) printer **(**Kulzer GmbH, Indiana, USA).

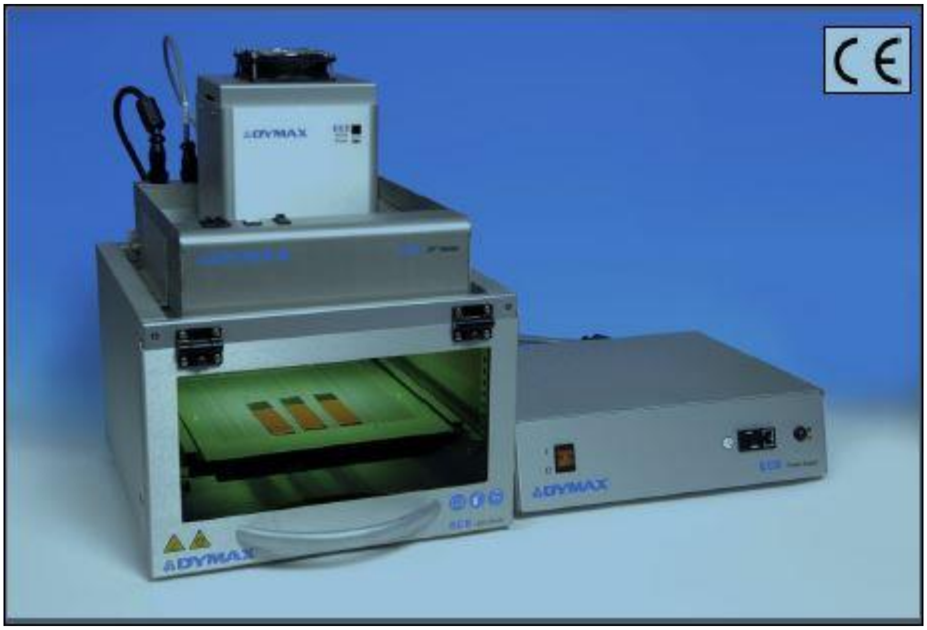

Figure 3. Dymax ECE 5000 UV light curing unit (Dymax corporation, Torrington, CT, USA).

Group II:

A polymethyl methacrylate (PMMA) billet with A1 shade was selected. The PMMA billet was manufactured by Aidite® (Qinhuangdao) Technology Co., Ltd, China (Figure 4). The billets are fabricated using high-temperature injection modeling technology. The specimens were nested within the dense PMMA billet using the CAD file. The specimens were then milled in a 4-axis milling unit called Zenotec® mini Technik GmbH & Co. KG, Germany (Figure 5). After milling the discs were snapped off and edges smoothened with a rubber wheel.

Figure 4. PMMA billet manufactured by Aidite® (Qinhuangdao) Technology Co., Ltd, China.

Figure 5. Zenotec® mini Technik GmbH & Co. KG, Germany.

Group III:

30-disc shaped specimens were printed using a stereolithography (SLA) 3D printer (Formslab2 printer, Formslab, USA) (Figure 6 & 8) and acrylic ester resin used for fabricating provisional restorations of shade A1 (Nextdent C&B MFH, Nextdent® by 3D systems, USA). Post processing was done using an 96% alcohol solution in an ultrasonic bath for 3 minutes. Post cleansing, curing was carried out for 30 mins using a blue UV light chamber with a wavelength of 315-400 nm using the (LC- 3D Print Box, Nextdent® by 3D systems, USA) (Figure 7 & 9).

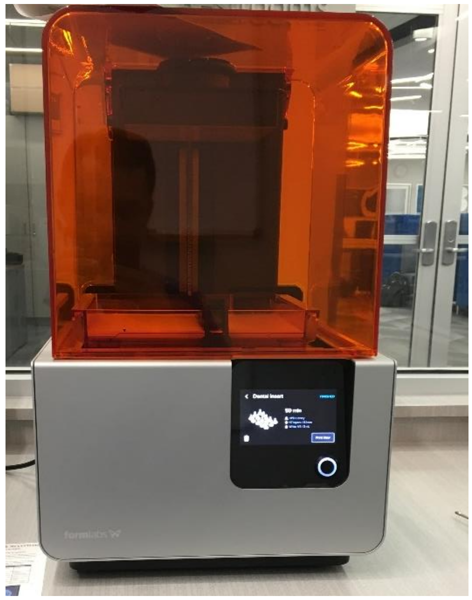

Figure 6. Formslab2 3D printer (Formslab, USA.)

Figure 7. LC- 3D Print Box (Nextdent® by 3D systems, USA).

Figure 8. Samples printed with SLA printer with excess resin prior to cleaning.

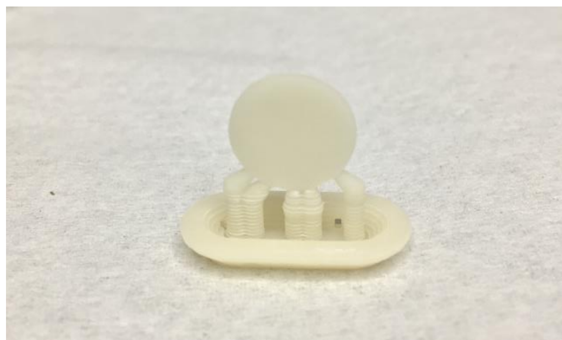

Figure 9. Acrylic ester resin (Nextdent C&B MFH, Nextdent® by 3D systems, USA) 3D printed sample after cleaning and curing.

2.2 Flexural strength measurement

Specimens were evaluated for biaxial flexural strength as follows. Disc specimens were centered and supported on three steel spheres of 1.6 mm diameter positioned 120 degrees apart on 8 mm diameter circle. The load was applied to the center of the specimen using a circular cylinder of hardened steel. The loading cylinder had a diameter of 1.2 mm with a flat end perpendicular to the axis of attachment to the upper member of the universal testing machine (Instron 8841, Instron Corporation, Norwood, MA, USA) (Figure 10). A thin mylar sheet was placed between the specimen surface and the loading cylinder to distribute the load uniformly (Figure 11). The specimens were then be loaded at a cross head speed of 0.5 mm/min till the specimen fracture occurs[9] (Figure 12). The testing was performed at room temperature conditions using an universal testing machine (Instron 8871, Instron Corporation, Norwood, MA, USA). The maximal tensile strength which corresponds to the biaxial flexural strength was calculated according to the equation suggested by the test standard (ASTM F394-78) as follows.

$S = -0.2387\ P(X-Y)d^2$

S = Maximal tensile strength (MPa)

P = Load at fracture

d = Specimen thickness (mm) at fracture origin

$X = (1+\eta)\ \ln (B/C)^2 + [(1-\eta)/2](B/C)^2$

$Y = (1+\eta)[1+\ln(A/C)^2] +(1-\eta)(A/C)^2$

η= Poissons ratio

A= Radius of the support sphere (mm)

B= Radius of the tip of the piston (mm)

C= Radius of the specimen (mm).

The Poisson’s ratio was assumed to be 0.24 for dental acrylics.

Figure 10. Universal testing machine (Instron 8871, Instron Corporation, Norwood, MA, USA).

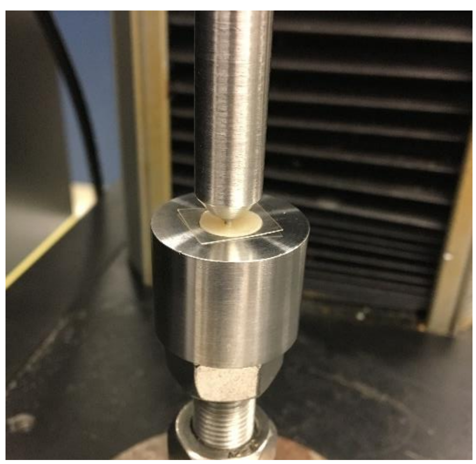

Figure 11. Thin mylar sheet was placed between the specimen surface and the loading cylinder.

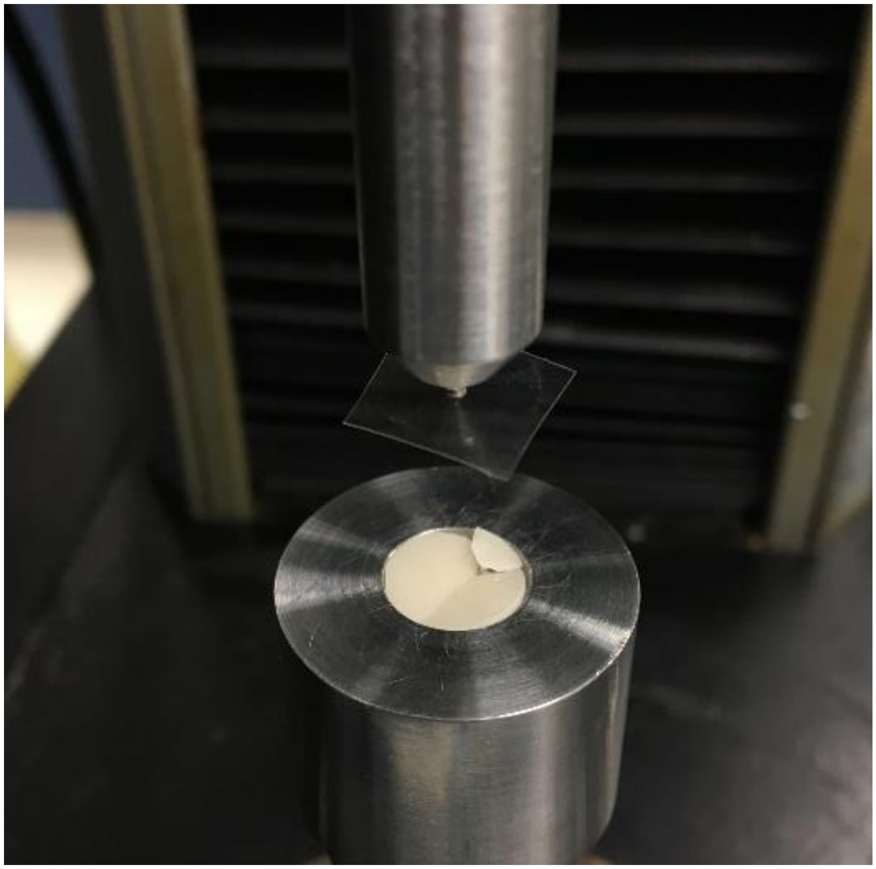

Figure 12. Fractured milled PMMA specimen.

2.3 Microhardness Measurement

The Vickers microhardness was used to determine the hardness number for each specimen group.[10] A force of 50g was applied via a diamond indenter at three distinct points on each specimen surface for 10 seconds. The indenter is a square based- pyramidal shaped diamond with a face angle of 136°. After force removal the impression diagonals are measured with light microscopy. The Vickers hardness values were calculated using the following formula, and the average group value were calculated for analysis. The Buehler micro hardness tester (Lake Bluff, Illinois, Chicago) was used for the measurement (Figure13).

$HV = 1854\ (p/d^2)$

Where:

1854 = constant value of equation based upon the specific geometry of the indenter.

p = applied force (Kg)

d = mean diagonal of the impression (mm)

Figure 13. The Buehler micro hardness tester.

2.4 Translucency Parameter (TP)

Once the samples were obtained, translucency was measured using CIE L*a*b* (Commission International L' Eclairage) parameters against white and black backgrounds using a scanning spectrophotometer (Color-Eye 7000A, Gretag Macbeth Instruments Corp., New Windsor, N.Y., USA) (Figure 14). The aperture size of the device was a 3 x 8 mm rectangular and the measuring geometry was 8°. The translucency parameter was calculated for each specimen using the formula below.[11]

$$TP= [(L^*b - L^*w)^2 + (a^*b - a^*w)^2 + (b^*b - b^*w)^2]^{1/2}$$

Where L*w, a*w and b*w belong to the white and L*b, a*b and b*b belong to the black background respectively. L* indicates lightness, a* indicates the green-red axis (-a: green and +a: red) and b* indicates the yellow-blue axis (-b: blue and +b: yellow) of each specimen.

The difference between the two readings gives the translucency parameter (TP) for each sample.[11] The TP readings obtained were compared with different groups to determine significance.

Figure 14. Scanning spectrophotometer (Color-Eye 7000A, Gretag Macbeth Instruments Corp., New Windsor, N.Y., USA).

2.5 Gloss

The gloss measurements of the samples were measured using a gloss meter (Novo-Curve, Rhopoint Instruments, East Sussex, UK) (Figure 15) using a 60-degree geometry. Three readings were made at 90-degree orientations and average value was calculated.[12]

Figure 15. Gloss meter (Novo-Curve, Rhopoint Instruments, East Sussex, UK).

After testing, selected specimens were prepared to be observed under scanning electron microscope (Figure 16).

Figure 16. Specimens prepared for scanning electron microscopy.

Chapter 3

Results

Univariate and bivariate statistics were calculated for all study variables. The data was reviewed for outliers and missing data. Appropriate data transformations were applied as necessary. Prior to the analysis the assumption of equal variance and normality was tested, and appropriate adjustments were made as necessary. A fixed-effect, one-way ANOVA with Tukey HSD pair-wise comparisons was employed to answer the research question. R 3.4.6 statistical software (RStudio, Inc, Boston USA) was used for the analysis of data. Results of the statistical tests were considered significant when p values were <0.05.

Fracture toughness:

In this study, the biaxial flexural strength was recorded and compared amongst different groups and tested for significance. The descriptive statistics are presented in Table 1.

Table 1. Summary Statistics for Flexural Strength (MPa)**.**

	Mean	St. Dev.	Min	Max
Printed Urethane Methacrylate	101.61	18.75	52.00	120.00
Milled Polymethyl Methacrylate (PMMA).	136.94	18.02	110.10	183.70
Printed Acrylic Ester Resin	98.37	6.52	84.30	108.50

Printed Urethane Methacrylate = Dentca™; Milled Polymethyl Methacrylate (PMMA) = Aidite®; Printed Acrylic Ester Resin = Nextdent®.

There was a significant effect of milling (PMMA group) on flexural strength at the $p<.05$ level for the three conditions [$F(2, 82) = 55.45$, $p < 0.001$]. There was no significant effect amongst the two groups which had printed provisionals on the flexural strength. Table 2 depicts the pairwise comparisons for the flexural strengths. Figure 17 depicts the blue bars as confidence intervals for the means for the flexural strength, and the red arrows are for the comparisons among them. If an arrow from one mean overlaps an arrow from another group, the difference is not significant.

Table 2. Pairwise Comparisons for Flexural Strength (MPa).

Group		Group	Difference	Lower 95% CI	Upper 95% CI	P-Value
Printed Acrylic Ester Resin	vs	Milled Polymethyl Methacrylate (PMMA)	-38.56	-46.43	-30.69	<.0001
Printed Acrylic Ester Resin	vs	Printed Urethane Methacrylate	-3.23	-11.18	4.71	0.705
Milled Polymethyl Methacrylate (PMMA).	vs	Printed Urethane Methacrylate	35.33	27.25	43.41	<.0001

Printed Urethane Methacrylate = Dentca™; Milled Polymethyl Methacrylate (PMMA) = Aidite®; Printed Acrylic Ester Resin = Nextdent®.

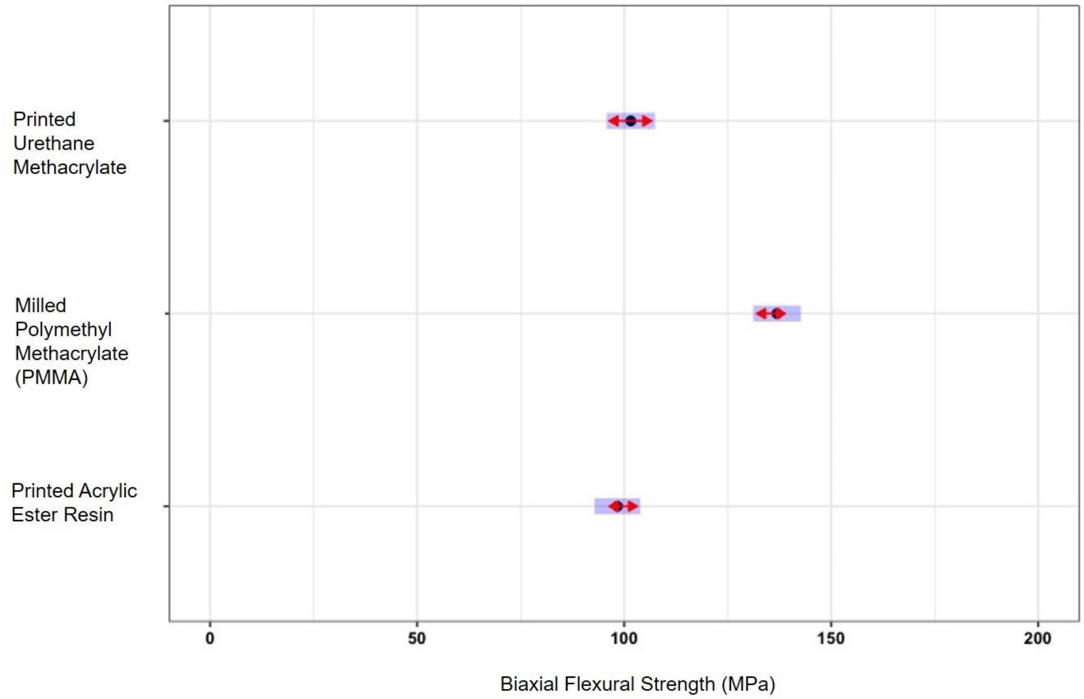

Figure 17. Confidence intervals for the means of the biaxial flexural strength values.

Translucency Parameter (TP):

There was a significant effect of milling (PMMA group) on translucency at the $p < 0.05$ level for the three conditions [$F(2, 87) = 373.6$, $p < 0.001$]. Descriptive statistics are presented in Table 3. Table 4 shows the Tukey pairwise comparisons for translucency parameter. Figure 18 depicts the blue bars as confidence intervals for the means for Translucency, and the red arrows are for the comparisons among them. If an arrow from one mean overlaps an arrow from another group, the difference is not significant.

Table 3. Summary Statistics for Translucency Parameter.

	Mean	St. Dev.	Min	Max
Printed Urethane Methacrylate	6.30	0.5	4.4	7.10
Milled Polymethyl Methacrylate (PMMA).	3.80	0.2	3.40	4.10
Printed Acrylic Ester Resin	4.35	0.3	3.80	5.20
Printed Urethane Methacrylate = Dentca™; Milled Polymethyl Methacrylate (PMMA) = Aidite®; Printed Acrylic Ester Resin = Nextdent®.				

Table 4. Pairwise Comparisons for Translucency Parameter.

Group		Group	Difference	Lower 95% CI	Upper 95% CI	P-Value
Printed acrylic ester resin	vs	Milled Polymethyl Methacrylate (PMMA).	0.60	0.41	0.78	<.0001
Printed acrylic ester resin	vs	Printed Urethane Methacrylate	-1.91	-2.10	-1.72	<.0001
Milled Polymethyl Methacrylate (PMMA).	vs	Printed Urethane Methacrylate	-2.51	-2.69	-2.32	<.0001
Printed Urethane Methacrylate = Dentca™; Milled Polymethyl Methacrylate (PMMA) = Aidite®; Printed Acrylic Ester Resin = Nextdent®.						

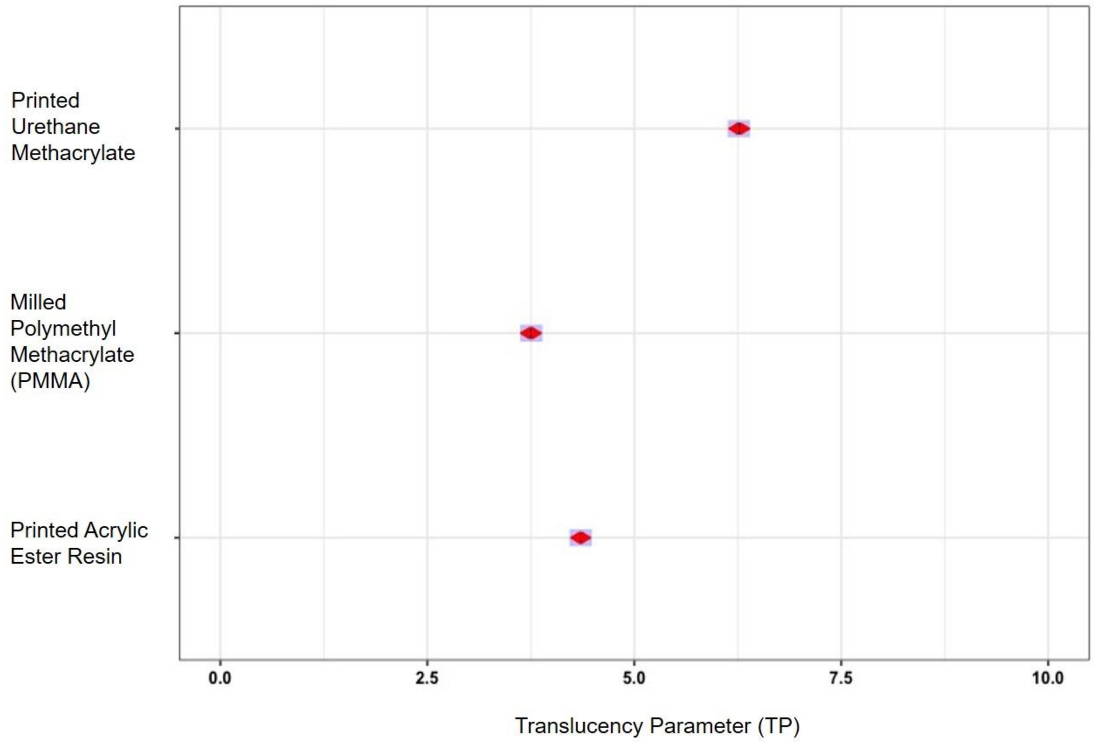

Figure 18. Confidence intervals for the means of the Translucency Parameter values.

Hardness:

There was a significant effect of milling (group) on hardness at the $p<.05$ level for the three conditions [$F(2, 87) = 99.19$, $p < 0.001$]. Descriptive statistics are presented in Table 5. Table 6 shows the Tukey pairwise comparisons for hardness values. Figure 19 depicts the blue bars as confidence intervals for the means for hardness, and the red arrows are for the comparisons among them. If an arrow from one mean overlaps an arrow from another group, the difference is not significant.

Table 5: Summary Statistics for Hardness Values

	Mean	St. Dev.	Min	Max
Printed Urethane Methacrylate	9.71	1.2	7.1	11.00
Milled Polymethyl Methacrylate (PMMA).	28.5	9.1	18.30	58.10
Printed Acrylic Ester Resin	14.82	1.40	12.30	18.30
Printed Urethane Methacrylate = Dentca™; Milled Polymethyl Methacrylate (PMMA) = Aidite®; Printed Acrylic Ester Resin = Nextdent®.				

Table 6: Pairwise Comparisons for Hardness Values

Group		Group	Difference	Lower 95% CI	Upper 95% CI	P-Value
Printed Acrylic Ester Resin	vs	Milled Polymethyl Methacrylate (PMMA).	-13.67	-16.38	-10.97	<.0001
Printed Acrylic Ester Resin	vs	Printed Urethane Methacrylate	5.11	2.41	7.81	0.001
Milled Polymethyl Methacrylate (PMMA).	vs	Printed Urethane Methacrylate	18.78	16.08	21.49	<.0001
Printed Urethane Methacrylate = Dentca™; Milled Polymethyl Methacrylate (PMMA) = Aidite®; Printed Acrylic Ester Resin = Nextdent®.						

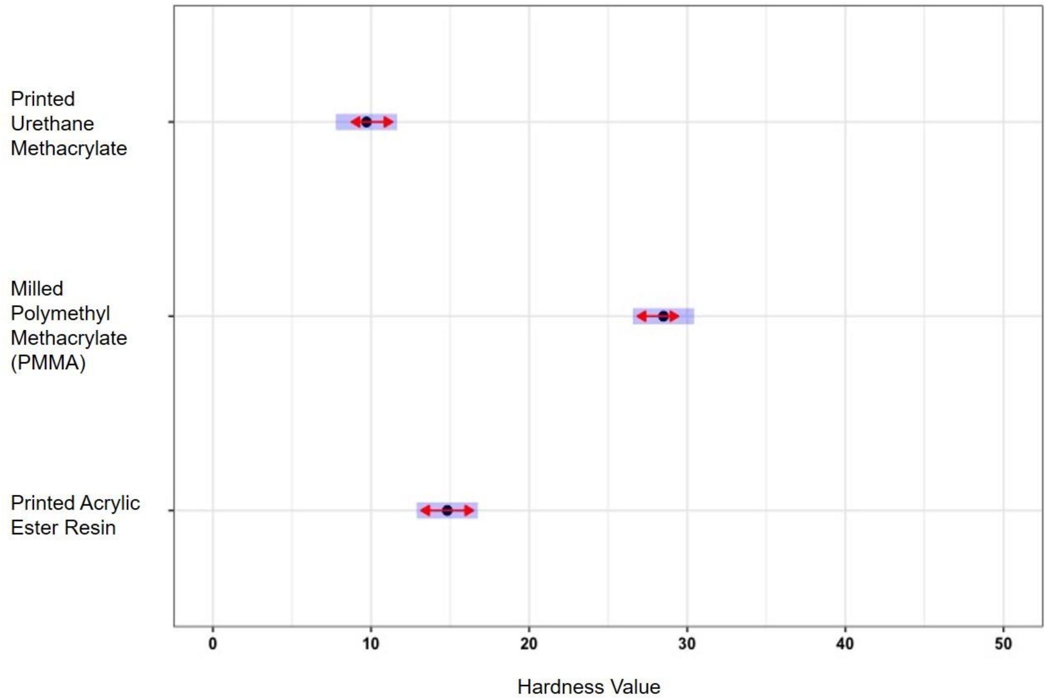

Figure 19. Confidence intervals for the means of the hardness values.

Gloss:

There was a significant effect of milling (group) on Gloss at the $p<.05$ level for the three conditions [$F(2, 87) = 281.3$, $p < 0.001$]. Descriptive statistics are presented in Table 7. Table 8 shows the Tukey pairwise comparisons for Gloss. Figure 20 depicts the blue bars as confidence intervals for the means for Gloss, and the red arrows are for the comparisons among them. If an arrow from one mean overlaps an arrow from another group, the difference is not significant.

Table 7: Summary Statistics for Gloss Values (GU).

	Mean	St. Dev.	Min	Max
Printed Urethane Methacrylate	28.8	8.5	15.9	48.10
Milled Polymethyl Methacrylate (PMMA).	3.9	0.6	2.7	5.7
Printed Acrylic Ester Resin	1.65	0.16	1.40	2.00
Printed Urethane Methacrylate = Dentca™; Milled Polymethyl Methacrylate (PMMA) = Aidite®; Printed Acrylic Ester Resin = Nextdent®.				

Table 8. Pairwise Comparisons for Gloss.

Group		Group	Difference	Lower 95% CI	Upper 95% CI	P-Value
Printed Acrylic Ester Resin	vs	Milled Polymethyl Methacrylate (PMMA).	-2.25	-4.74	0.23	0.184
Printed Acrylic Ester Resin	vs	Printed Urethane Methacrylate	-27.11	-29.60	-24.62	<.0001
Milled Polymethyl Methacrylate (PMMA).	vs	Printed Urethane Methacrylate	-24.86	-27.34	-22.37	<.0001
Printed Urethane Methacrylate = Dentca™; Milled Polymethyl Methacrylate (PMMA) = Aidite®; Printed Acrylic Ester Resin = Nextdent®.						

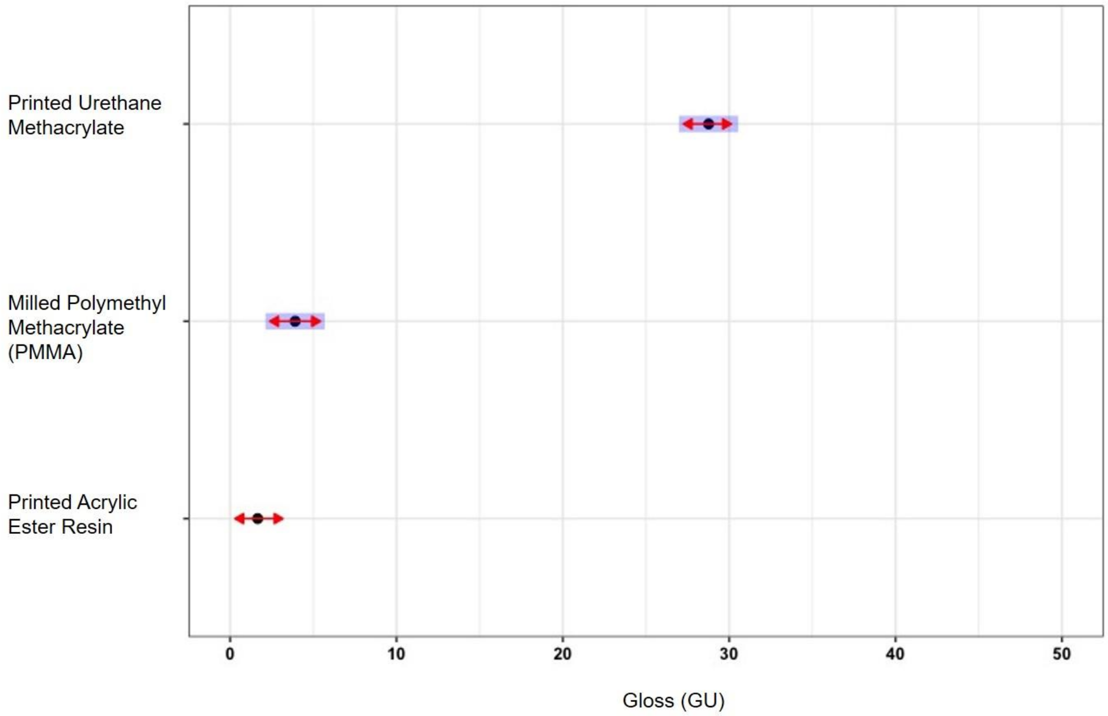

Figure 20. Confidence intervals for the means of the gloss values.

Chapter 4

Discussion

This study was intended to evaluate physical and optical properties of provisional resin materials fabricated by CAD CAM technology. As milling technology is increasingly becoming the norm, the world of 3D printing is ever expanding as well. According to the 2018 Wohler's[23] report 135 companies produced and sold industrial 3D printing systems in 2017, up from 97 companies in 2016. As of 2018, 528,952 desktop 3D printers have been sold, compared to 278,000 in 2015. 3D printing has expanded from being used for light activated resins to now being capable of printing certain metals and ceramics. As the dental profession is increasingly incorporating digital technology, our study was designed to better understand the physical and optical properties of provisional restorative resins fabricating by these methods.

Provisional restorations have been fabricated from different materials, but acrylic has been by far the most common. Digholkar et al[15] in their study found that heat processed acrylic resins have shown to have strength in the range of 100 MPa. Provisionals restorations fabricated by milling prefabricated PMMA billets have strengths in a similar range. In the same study, provisionals fabricated using rapid prototyping technology yielded inferior results as compared to conventional and milled restorations with strengths in range of 80 MPa. The results of our study yielded similar results, with provisionals fabricated by 3D printing yielding lower strength values as opposed to the milled group. However, the strength values obtained in our study were in range of 100 MPa for the printed groups and 138

MPa for milled group, with the latter being significantly higher. Scanning electron microscopic imaging of the fractured surfaces of the specimens from our study corroborated this finding (Figure 21). Our study however, found no statistically significant difference in the ultimate fracture strength values between provisionals printed using acrylic ester resin or urethane methacrylate.

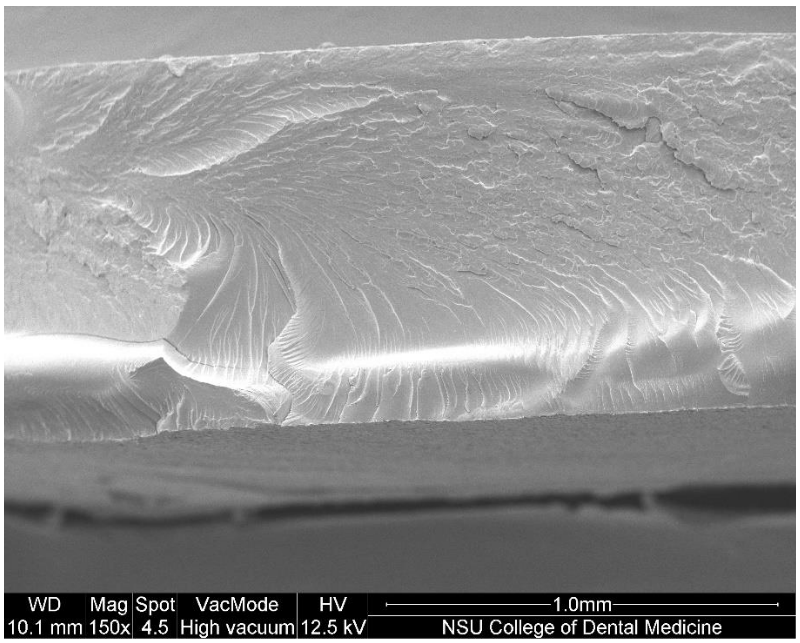

Figure 21. SEM image of the fractured surface of the milled PMMA specimen. The tortuous morphology seen on the fracture surface is a result of higher levels of energy absorption during fracture, which translates into higher measured strength.

On examination of the stress strain curves, it was noticed that the acrylic ester resin group (Nextdent C&B MFH, Nextdent® by 3D systems, USA) showed higher elastic deformation and little plastic deformation prior to fracture. This suggested a more brittle tendency of the resin during fracture. Scanning electron microscopy of the fractured surface of these specimens revealed multiple cracks propagating through the specimen and an overall smoother fracture surface (Figure 22).

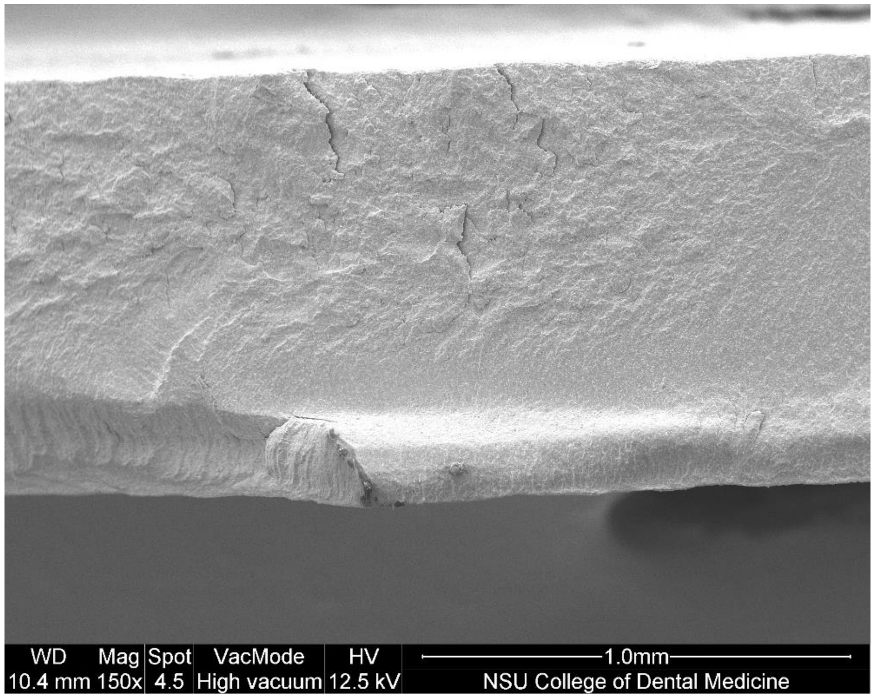

Figure 22. SEM image of the fractured surface of the printed acrylic ester resin specimen (Nextdent C&B MFH, Nextdent® by 3D systems, USA).

The urethane methacrylate group (Dentca™ Inc, California, USA) however, showed a lower elastic deformation and prolonged plastic deformation with an abrupt increase in elastic deformation just prior to fracture. This suggests a more resilient material with a tendency to deform before breaking. Scanning electron microscopy of the fractured surface of these specimens revealed surface cracks propagating superficially through the specimen with the bulk of the structure remaining unaffected (Figure 23).

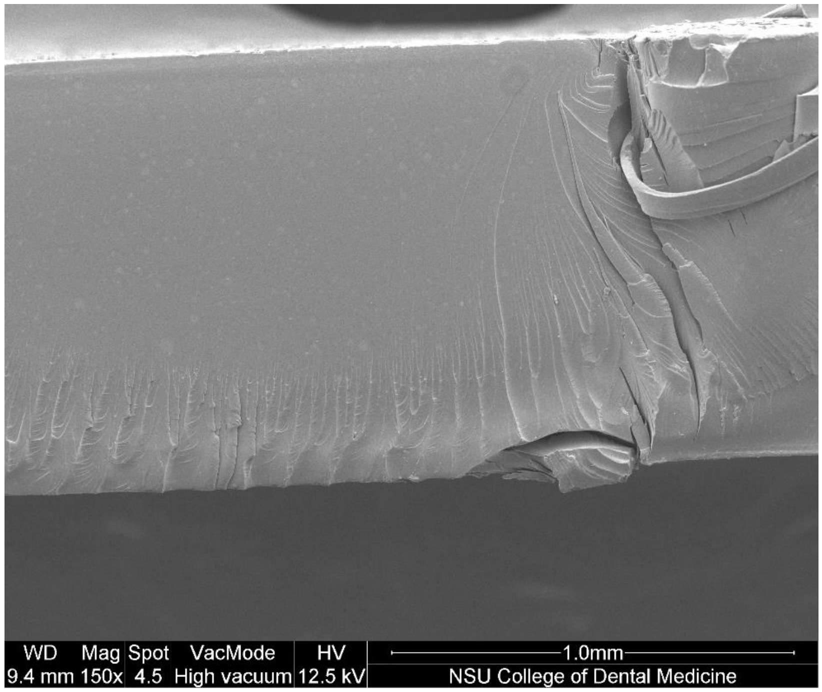

Figure 23. SEM image of the fractured surface of the urethane methacrylate group (Dentca™ Inc, California, USA). The smooth fracture surface morphology is indicative of a low strength fracture.

The milled polymethyl methacrylate (PMMA) (Aidite® Technology Co., Ltd, China) group showed a similar stress strain curve when compared to the urethane methacrylate group, except for having higher fracture loads. Similar results were seen from a study by Tahayeri et al,[4] who also compared the degree of conversion of printed resins and reported it to be higher than auto polymerizing resins.

Translucency of a restoration is its ability to partially allow light to pass through it. It thus lies in an area of complete transparency to total opacity. Thickness, refractive index, and filler particles (structure) are a few variables that affect the translucency of dental materials.[24] This property allows the restoration to blend in with the adjacent teeth or restorations. Since provisional restorations serve as an esthetic blueprint of the final restorations, the translucency should bear close resemblance to the teeth and/or final restorations. Hasegawa et al[25] in their study reported translucency to be around 5 in the cervical region and around 15 in the incisal region of natural incisors. Translucency parameter (TP) is a measure of translucency where color difference of the sample is measured against a white and a black background. A zero value would indicate a completely opaque material while a value of 100 denotes a completely transparent material.

Our study showed a statistically significant difference in translucency amongst all three groups with printed urethane methacrylate group (Dentca™ Inc, California, USA) being the most translucent with a mean of 6.3 followed by printed acrylic ester resin (Nextdent C&B MFH, Nextdent® by 3D systems, USA) with a mean value of 4.4. Scanning electron microscopy of the surface of these specimens revealed a homogenous surface for the urethane methacrylate group (Dentca™ Inc, California, USA; Figure 24).

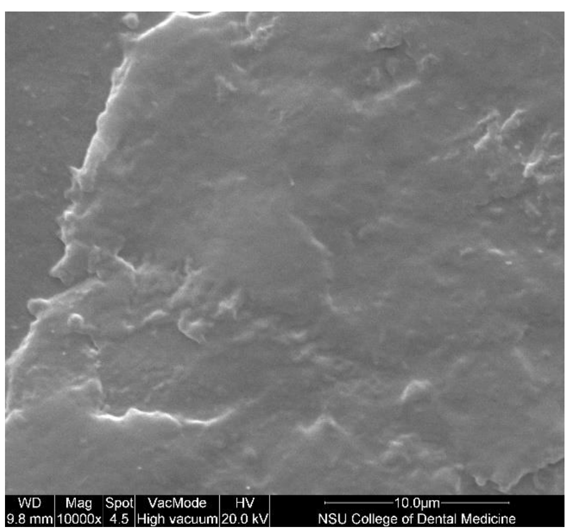

Figure 24. SEM image of the surface of the urethane methacrylate group (Dentca™ Inc, California, USA).

The printed acrylic ester resin (Nextdent C&B MFH, Nextdent® by 3D systems, USA) surface however was rougher & more irregular (Figure 25). This would cause considerable scatter of light as it travels through it thereby reducing the translucency.

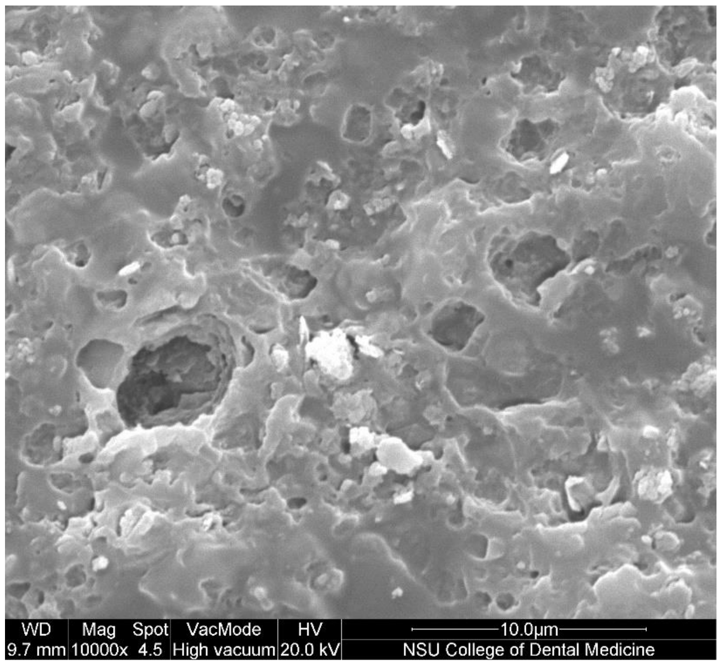

Figure 25. SEM image of the surface of the printed acrylic ester resin specimen (Nextdent C&B MFH, Nextdent® by 3D systems, USA).

Milled polymethyl methacrylate (PMMA) (Aidite® Technology Co., Ltd, China) was the most opaque amongst the three with a mean value of 3.8. Although scientific proof is lacking, it is our opinion, that the incremental layering of printed resins permits more light transmission as opposed to a billet which is highly dense with intertwined long polymeric chains. The dense and long polymeric chains tightly intertwined with each other allow for more scatter thereby limiting the light transmission. A scanning electron microscopic image of the surface of a milled PMMA specimen shows considerable irregularity on the milled surface, with little structural imperfections observable, perhaps as a result of dense structure of the starting billet (Figure 26).

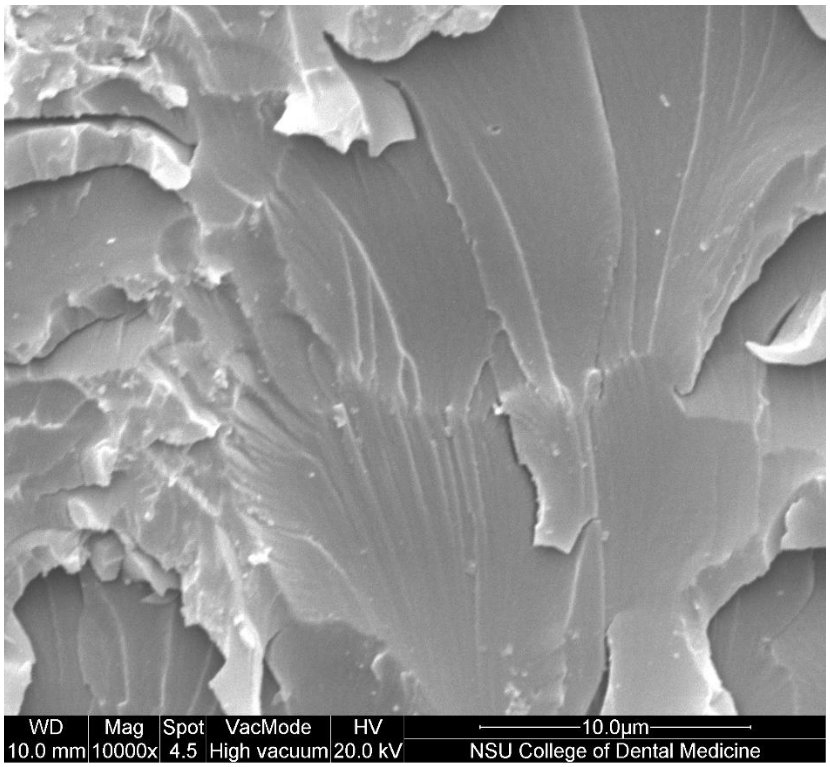

Figure 26. SEM image of the surface of the milled PMMA specimen (Aidite® Technology Co., Ltd, China).

Hardness is another property of a material which can be related to density, especially for polymers. It can also be assumed that a harder material could be more wear resistant. Our study indicated that there was a significant difference between the microhardness values tested for all the groups. The milled polymethyl methacrylate (PMMA) (Aidite® Technology Co., Ltd, China) group had the highest hardness value, with a mean of 28.1. This could be attributed to the dense polymeric structure formed during manufacturing of the billet. These values are similar to a previously reported study.[15] Printed acrylic ester resin (Nextdent C&B MFH, Nextdent® by 3D systems, USA) was second hardest in the groups tested with an average microhardness value of 14.8. This can also be linked to its stress strain graph indicating a brittle, stiff nature, which translates into higher hardness. The urethane methacrylate group (Dentca™ Inc, California, USA) had the lowest microhardness value with an average of 9.7. The stress strain graph indicates it as a more resilient, but less stiff material, supporting this finding. These hardness findings are contradictory to the findings by Digholkar et al.[15] The difference could be attributed to different fabrication methodology and different materials tested.

The property of a material to reflect light is termed gloss. Gloss is an important characteristic which provides a life like appearance to a restoration. In our study, we aimed to study the gloss of the surface of the specimens, without any finishing and polishing procedures post fabrication. Gloss values are expressed as GU units and range from 0-100, with zero denoting a non-reflective surface and 100 being that of a reflective glass with refractive index of 1.567.[26] Our study indicated a statistically significant difference between the gloss values of urethane methacrylate resin group (Dentca™ Inc, California, USA) and the printed acrylic ester resin (Nextdent C&B MFH, Nextdent® by 3D systems, USA) and the milled polymethyl methacrylate (PMMA) resin. Difference in gloss values of printed acrylic ester resin (Nextdent C&B MFH, Nextdent® by 3D systems, USA) and milled polymethyl methacrylate (PMMA) were not significant, with mean values of 1.7 and

3.9 respectively. Since the milled PMMA group samples were fabricated by milling, the cut of the bur would dictate the surface reflectivity, resulting in a low gloss value. The printed acrylic ester resin (Nextdent C&B MFH, Nextdent® by 3D systems, USA) samples are kept in an ultrasonic alcohol bath which would effectively remove any uncured resin from the surface. This would possibly be the reason for low gloss values. The urethane methacrylate group (Dentca™ Inc, California, USA) group showed high gloss values with a mean of 28.8. Since this group employed a curing process under glycerol, it could leave a thin skin of uncured resin on the surface which gets cured in a more protected environment leading to the higher gloss value.

The aim of this study was to compare the physical properties of these materials as they are manufactured. Further testing to simulate oral conditions would give us additional insight on the practical applications of these materials.

Chapter 5

Conclusion

Within the limitations of this study, the following conclusions were drawn.

1. Results indicate that milled polymethyl methacrylate (PMMA) has superior flexural strength compared to 3D printed resins.
2. Results indicate that milled polymethyl methacrylate (PMMA) has superior microhardness compared to 3D printed resins.
3. Printed urethane methacrylate showed significantly better translucency when compared to milled PMMA or resins with acrylic esters.
4. Printed urethane methacrylate also showed significantly better gloss values when compared to milled PMMA or resins with acrylic esters.

Each approach to creating provisional restorations displayed advantages and disadvantages when comparing characteristics of clinical interest. Although the specimens fabricated by milling technology have superior mechanical properties now, 3D printing is a vastly growing field and continued research and innovations are emerging rapidly.

Our study aims to create a benchmark for future studies on the subject of 3D printing.

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