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COMPARISON OF FLEXURAL STRENGTH AND POROSITY

OF COMMON 3D PRINTED DENTURE BASE ACRYLIC RESINS

A THESIS

SUBMITTED TO THE GRADUATE DENTAL EDUCATION

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE

MASTER OF ORAL BIOLOGY

BY

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ADVANCED EDUCATION IN GENERAL DENTISTRY

FORT HOOD, TEXAS

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Introduction

According to the American College of Prosthodontists, approximately 36 million Americans are completely edentulous and 120 million Americans are missing at least a single tooth.[1] Due to increased life expectancy, these numbers are projected to increase over the next 20 years. While edentulism is more common amongst vulnerable groups such as the elderly and economically disadvantaged, the effects of oral disability continue to impact all demographics and socioeconomic statuses. Although the consequences of losing teeth initially seem to solely affect the individual involved, the correlation between edentulism and risk for chronic disease such as obesity, diabetes, coronary artery disease and some forms of cancer[1] ultimately contribute to society's burgeoning health care burden.

Mankind's millennia-long conundrum of replacing missing teeth has been well-documented in the discovery of ancient dental prostheses in various cultures throughout history. Some of the earliest dentures were made from ivory from various animals, wood, porcelain, and even cadaver teeth. The invention of vulcanized rubber in the 1860s marked a key turning point in denture fabrication from natural to man-made materials. The most significant contribution to the denture industry came in the 1930s by Dr. Walter Wright with the invention of polymethylmethacrylate (PMMA) which quickly replaced rubber as the denture-base material of choice. PMMA outperformed vulcanized rubber on all fronts offering improved esthetics, biocompatibility, wearability, cleansability, dimensional stability, handling and cost. While no other material has yet to replace PMMA as the denture-base material of choice, various fillers, polymer materials and processing methods have been introduced over the years in an effort to continue to improve chemical and physical properties. The three most common conventional methods of denture fabrication include fluid resin (pour), compression molding (pack and pour), and injection molding techniques. Compression molding relies on the burning out of wax denture reproductions using gypsum models in gypsum compression forms. Injection molding involves the methodic introduction of flowable plastic into a flask under pressure using a special apparatus. While injection molding is the more costly option, it offers the combined advantages of heat-polymerization and reduced processing time, increasing accuracy and stability of the denture bases.[3]

The advent of CAD/CAM (computer-aided design/computer-aided manufacturing) digital technology in the 1970s provided the next groundbreaking advancement in full mouth rehabilitation through three-dimensional (3D) printing and milling capabilities. Printing involves rapid prototyping (RP) through an additive manufacturing process while milling relies on a computerized numeric control subtractive process.[4] The major advantage of printing over milling is a more sustainable fabrication method by conservation of denture resin material.[4] With the increasing popularity and accessibility of 3D dental fabrication technologies, individuals who suffer from complete edentulism now stand to significantly benefit from near-immediate denture fabrication. These recent advancements in digital dentistry have reduced denture fabrication in both time and cost. What once required five-to-six appointments and cost $50 per unit, can now be done in a mere two appointments[5] at the reduced cost of $10 per unit. In the military environment 3D denture fabrication capabilities has many implications.

Faster denture fabrication can help improve dental readiness by significantly reducing time spent in oral rehabilitation, thus affording edentulous Soldiers a quicker turn-around for improving quality of life and resuming war-fighting status. Due to its transportability, this technology also has the potential to be employed in combat zones, providing the capability for same-day prostheses fabrication for Soldiers who encounter facial and oral trauma.

While time and finances are key determinants when selecting proper treatment modalities for dentures, quality and durability of materials are equally important. Flexural strength represents a material's potential to resist catastrophic failure which is paramount in successful, long-term denture use[4]. In order to endure repeated masticatory loads in the oral cavity denture materials must be able to exhibit high resistance to plastic deformation and fatigue resistance. The flexural strength of a resin material is directly related to the degree of polymerization that is achieved during processing. Those resin materials that undergo a higher degree of conversion during polymerization generally demonstrate a higher flexural strength and less dimensional change. In theory, due to their 'preformed' nature, printed and milled materials are less prone to porosities, dimensional changes and therefore, less prone to breakage. While denture failures over the years have been linked to various design features and material choices, utilizing a denture base material that demonstrates high bending stress properties lends itself to an overall lower rate of catastrophic failure, ultimately reducing denture costs in the form of both time and money.

As the popularity of CAD/CAM denture technology has grown in recent years, so has community interest in the advantages and disadvantages of the digital process. A laboratory study conducted by Goodacre et al found that when compared to traditional techniques the CAD/CAM process is more accurate and a more reproducible fabrication technique.[8] Srinivasan et al performed an in vitro study to compare the difference in trueness between 3D-printed dentures and CAD-CAM milled. This study found that the CAD-CAM milled dentures were superior in trueness of the intaglio surfaces compared to the printed dentures.[8]
Kattadiyl et al discovered that digitally fabricated dentures had significantly higher retention, fit, and stability over conventional methods[8]. In this same study digital dentures also had higher average response scores from patients for efficiency of technique, mastication efficiency, comfort and retention. When Aguirre et al compared the flexural strengths of compression molded, injection molded, and CAD-CAM milled groups they found that flexural modulus and flexural strength were significantly higher in the milled group.[4] More recently a bench study awaiting publication by Fouda et al evaluated the flexural strength, elastic modulus and hardness of CAD-CAM milled, 3D printed and heat-polymerized dentures. While CAD-CAM milled out-performed its counterparts, the printed group's values were still above the clinically acceptable values.[9] The overarching trend in CAD/CAM denture fabrication indicates numerous advantages over conventional counterparts. The main advantages identified include decrease in clinical chair time and number of visits, digital archiving, significantly higher retention, less denture tooth movement, increased toughness, higher elastic modulus, and more favorable clinical and patient-centered outcomes.[8]

Prior to this project few, if any, studies have attempted a side-by-side comparison of flexural strength and porosity of common CAD/CAM 3D printed denture materials available in today's digital dentistry market. Since the first 3D printer was invented in 1983 and the first digital denture was printed in 2015[5], a myriad of 3D dental printers has surfaced in the market. There are currently fifteen commercially available dental 3D printers with eight different printing methods utilized among them[5], providing sufficient variability in product properties to merit closer evaluation. If CAD/CAM removable prostheses are to replace current conventional denture methods as the gold standard for treating edentulism then they must prove their value by not only decreasing chair-time and cost, but also by surpassing the minimum ISO standards for flexural strength (65 MPa) as well as other properties critical to long-term denture success.

The null hypothesis was that there would be no significant difference in porosity and flexural strength between the 3D printed denture acrylic group and the injection molded group. There would also not be any significant variation in flexural strength and percentage porosity within the three 3D printed materials group.

Purpose

The purpose of this study was to perform an in vitro, bench-top study comparing the flexural strength and porosity of three common 3D printed denture resin-base brands against the conventional injection-molded process. The injection molded material selected for the control group was Ivoclar IvoBase Hybrid (Ivoclar Vivadent, Liechenstein, Austria). The 3D brands selected for testing included Formlabs Denture Base Resin (Formlabs, Inc. Somerville, MA), Lucitone Digital Print™ 3D Denture Resin (Dentsply Sirona Prosthetics, York, PA), and DENTCA Denture Base II (DENTCA, Inc. Torrance, CA). The injection molded acrylic resin specimen were fabricated from 3D printed molds using Formlabs High Temperature Resin (Formlabs, Inc. Somerville, MA). (Table 1)

Table 1. Test Material Information

Product Name	Manufacturer	Fabrication Method	Composition
IvoBase Hybrid Polymer (control group)	Ivoclar Vivadent	Injection-molded using Ivoclar IvoBase Injector	>95% polymethylmacrylate
DENTCA Denture Base II	DENTCA Inc.	Digital Light Synthesis™ on Carbon® 3D printer	40-60% Methacrylate monomer 30-50% Diurethane dimethacrylate 3-10% Trimethylolpropane trimethacrylate <3% Initiator <1% Stabilizer < 0.4% Pigment
Lucitone Digital Print™ 3D Denture Resin	Dentsply Sirona Prosthetics	Digital Light Synthesis™ on Carbon® 3D printer	40-50% Urethane Methacrylate 40-50% Organic Methacrylate Monomer 1-5% Organic Acrylate Monomer <1.5% Photoinitiator
Formlabs Denture Base Resin	DENTCA	Stereolithography on Formlabs Form 3 3D printer	40-60% Bisphenol A dimethacrylate 30-50% Urethane dimethacrylate 5-10% Methacrylate monomer <3% Photoinitiator

Materials and Methods

In accordance with ISO 20795-1, rectangular specimen (64x10x3.3 mm) and cylindrical specimen (6x4 mm) were fabricated using Formlabs Denture Base Acrylic OP and Formlabs High Temperature Resin on a Formlabs Form 3 printer (Formlabs Inc. Somerville, MA). The Formlabs High Temperature Resin specimens were flasked using ISO Type III dental stone to make molds for the injection-molded specimen. The Formlabs High Temp Resin specimens were removed from the flasks prior to injecting with Ivoclar IvoBase Hybrid polymer on an IvoBase Injector (Ivoclar Vivadent, Liechenstein, Austria). The DentsplySirona Lucitone Digital Print™ 3D Denture Resin and DENTCA Denture Base II specimen were fabricated by a local commercial denture laboratory using a Carbon® printer (Model M2458, Carbon®, Redwood City, CA). Remaining printing attachments on the specimen were removed with 400 and 600 grit sanding paper by a single operator. After surface treatment, the 3D printed specimen were stored in deionized water at 37°C for 12 hours and placed in an ultrasonic (Elmasonic P) for 10 minutes prior to testing.

Figure 1: Upper left photo: unprocessed Formlabs Denture Resin samples; Upper right photo: unprocessed Formlabs High Temperature Resin samples; Lower left photo: ISO Type III dental stone flask mold made from Formlabs High Temperature Resin samples; Lower right photo: processed Ivoclar IvoBase Hybrid injection molded samples

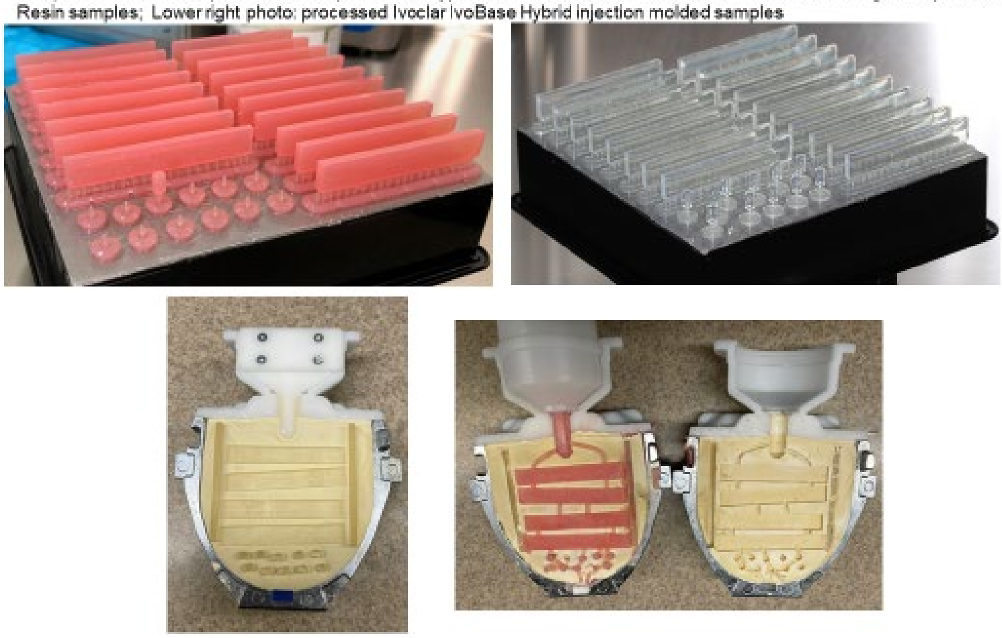
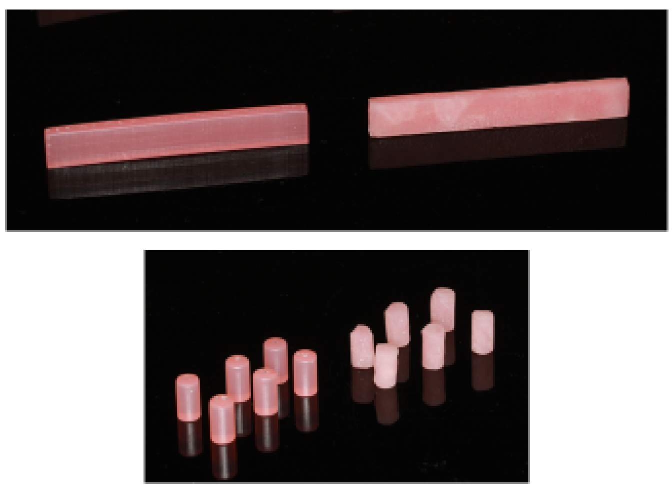


Figure 2: Rectangular and cylindrical samples of Formlabs Denture Base Resin and Ivoclar IvoBase Hybrid injection molded processed, trimmed, and lightly polished. (Formlabs on left, IvoBase on right)



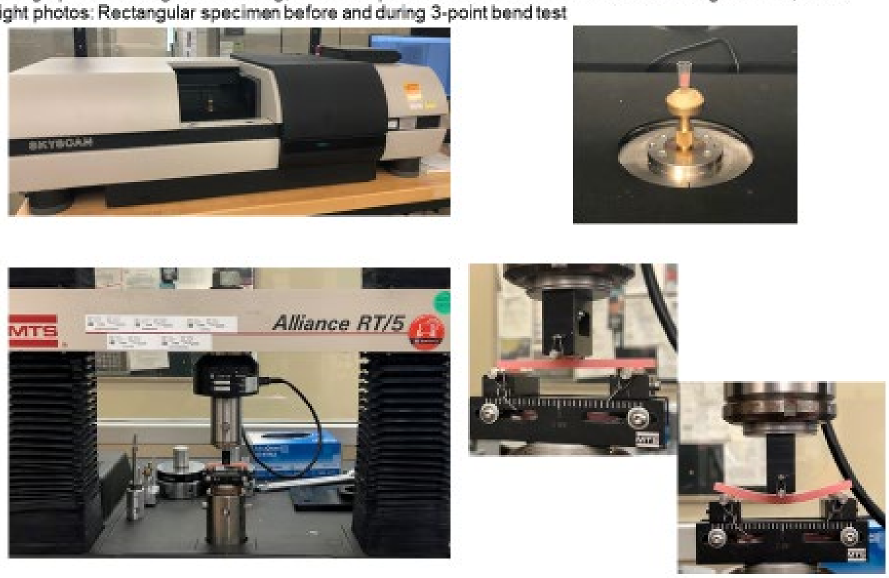
Rectangular specimen (DENTCA n=19, Lucitone n=20, IvoBase n=18, Formlabs n=18) were tested using a universal testing machine (Model 5543, Instron, Canton, MA, USA) at a crosshead speed of 5 mm/min. Each specimen was placed on a three-point bending test device, which is constructed with a 50 mm span length between the supporting rods, the central load was applied with a head diameter of 2 mm. The flexural strength (σ_{FS}, MPa) was obtained using the expression,

$$\sigma_{FS} = \frac{3Pl}{2bd^2},$$

where *P* is the loading force at the fracture point; *l* is the length of the support span (50 mm); *b* is the width; and, *d* is the thickness. Width and thickness measurements of the rectangular specimens was made using an electronic digital caliper (GA182, Grobet Vigor, Carlstadt, NJ, USA). The mean flexural strength and standard deviation were calculated. Flexural modulus was determined from the slope of the linear region of the load-deflection curve using the analytical software (Instron).

A micro-CT (SkyScan 1172, Bruker microCT, Billerica, MA) was used to analyze five cylindrical specimens from each group. Each specimen was scanned 180 degrees with a 0.4-degree rotational increment per frame using a source voltage and current of 70 kV and 141 µA, respectively. At each rotational degree, five scans were captured and averaged to give one projected frame. A total of 510 projections per specimen was acquired. These projected scans were then reconstructed into a three-dimensional volume with a voxel size of 7 µm and 2000 x 1048 pixels per slice, using a customized Feldkamp algorithm (NRecon v-1.7.4.6, Bruker, Billerica, MA). Image segmentation and analysis was performed using a proprietary software (CTAn v-1.18.9.0+, Bruker, Billerica, MA). Total volume of the sample and its volume porosity, percent porosity, and number of open and close pores was determined.

Figure 3: Upper left photo: Skyscan 1172 microCT machine; Upper right photo: Cylindrical specimen placed on high-precision stage for scanning; Lower left photo: Instron Model 5543 universal testing machine; Lower right photos: Rectangular specimen before and during 3-point bend test



Statistical Analysis

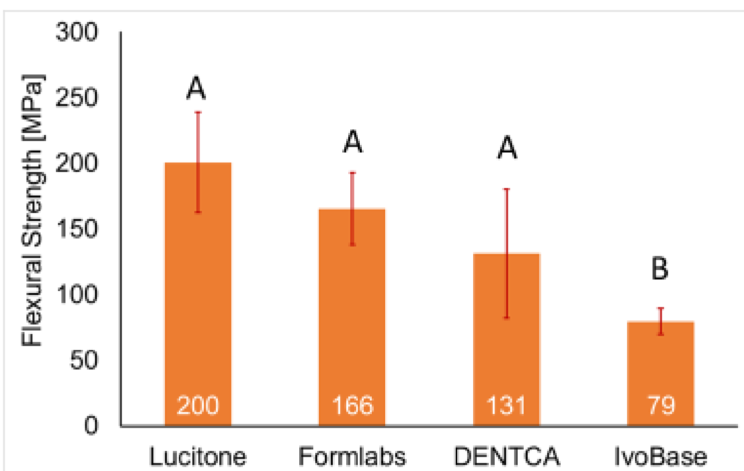
Statistical analysis using the Shapiro-Wilk test showed that the flexural strength and strain data were not normally distributed. The Levene test demonstrated unequal variances across the groups, therefore a Kruskall-Wallis test with Steel-Dwass post-hoc test were applied for statistical analyses. One-way ANOVA was conducted on porosity data due to its small sample size. Predictive statistics were performed using Weibull Analysis to determine Weibull modulus and characteristic strength of the rectangular specimen. The significance level for statistical tests was set at $\alpha = 0.05$ and $\alpha = 0.01$ was set as level for high statistical significance.

Results

Flexural Strength

The Lucitone group had the highest mean peak load of 200 N while the IvoBase group had the lowest mean peak load of 79 N. Amongst the four tested denture base acrylic resins, Lucitone revealed significantly higher flexural strength than Formlabs, DENTCA, and IvoBase. IvoBase demonstrated significantly lower flexural strength than the other three groups ($p<0.01$). DENTCA had the highest standard deviation and IvoBase the lowest. (Figure 4)

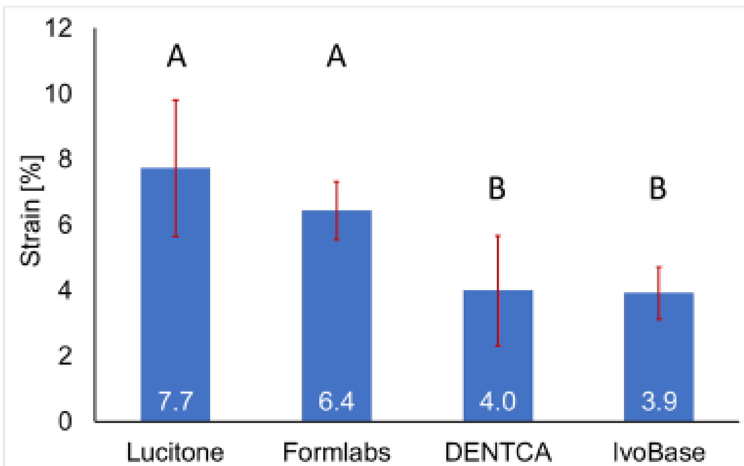
Figure 4: Amongst the four tested denture base acrylic resins, Lucitone demonstrated significantly higher flexural strength than Formlabs, DENTCA, and IvoBase. Bars with the different case letters are significantly different than each other ($p < 0.01$).



Flexural Strain

The Lucitone group demonstrated the highest mean strain of 7.7% while IvoBase demonstrated the lowest mean strain of 3.9%. Amongst the four tested denture base acrylic resins, Lucitone and Formlabs demonstrated significantly higher flexural strain than IvoBase and DENTCA. However, the flexural strains between Lucitone and Formlabs are not significantly different from each other. Lucitone and Formlabs groups showed significantly different values compared to the DENTCA and IvoBase groups (p<0.01). Lucitone had the highest standard deviation and IvoBase and Formlabs had the lowest. (Figure 5)

Figure 5: Amongst the four tested denture base acrylic resins, Lucitone and Formlabs demonstrated significantly higher flexural strain [%] than IvoBase and DENTCA. However, the flexural strains between Lucitone and Formlabs are not significantly different from each other. Bars with the different case letters are significantly different than each other ($p < 0.01$).



Porosity

The Lucitone group had the highest porosity percentage of 0.26%. The DENTCA, IvoBase, and Formlabs groups all had a mean porosity percentage of 0.18%. While Lucitone demonstrated significantly higher percent porosity compared to DENTCA, Formlabs, and IvoBase all groups had averages less than .3% which was not statistically significant. (Figure 6 and Figure 7)

Figure 6: Amongst the four tested denture base acrylic resins, Lucitone demonstrated significantly higher porosity than Formlabs, DENTCA, and IvoBase. Bars with the different case letters are significantly different than each other ($p < 0.01$).

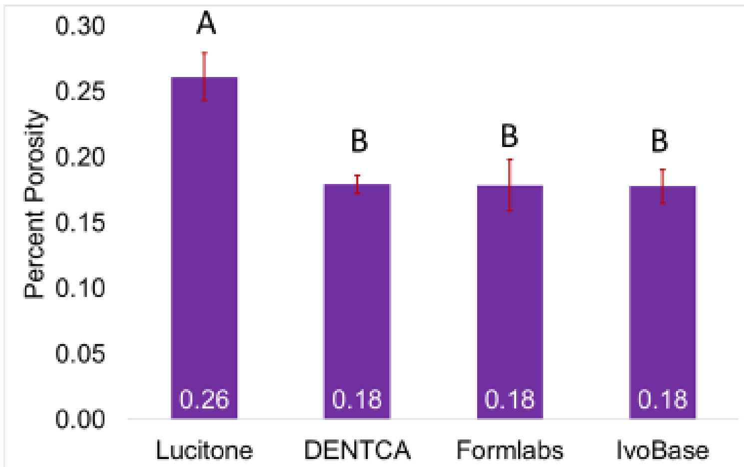
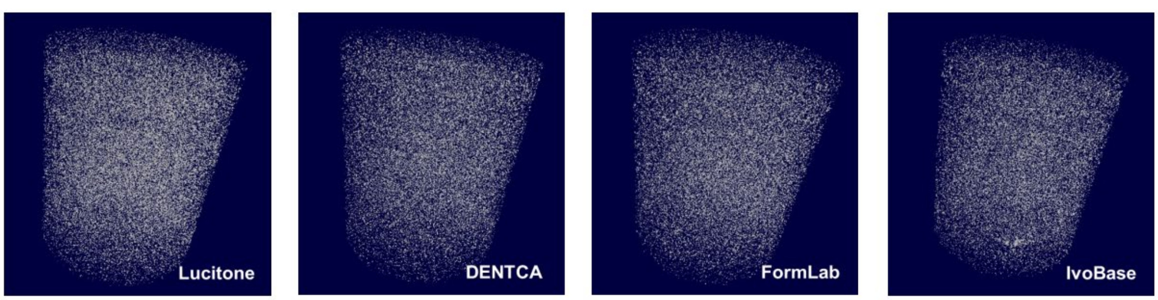
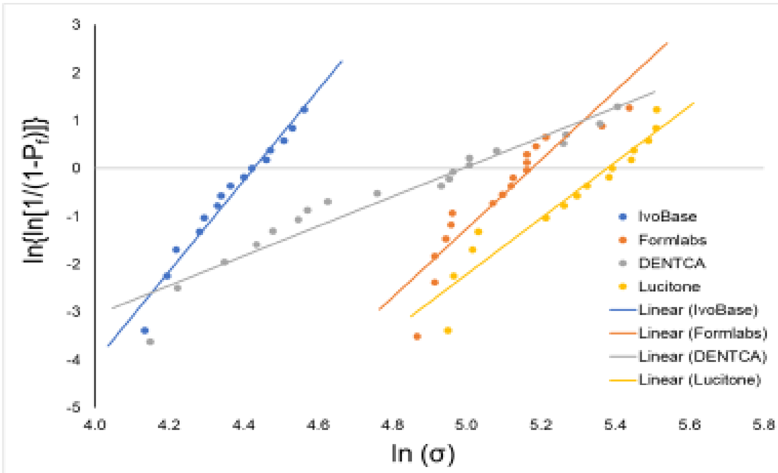


Figure 7: MicroCT scans of the four tested denture base acrylic resins showing porosity.



Weibull Modulus and Characteristic Strength
Lucitone demonstrated the highest characteristic strength at 216.5 MPa. IvoBase had the highest Weibull modulus value at 9.5 and the lowest compressive strength at 83.7. DENTCA showed the lowest Weibull Modulus at 3.1. (Figure 8)

Figure 8: Weibull reliability for the four tested denture base acrylic resins is plotted. Lucitone demonstrated the highest characteristic strength, mirroring similar findings as from the three-point flexural test. The characteristic strength is defined as the stress (σ) at which 63.2% of the tested material population has failed. P_f represents the probability of failure. Weibull modulus describes how defects within a material is distributed throughout the entire material volume. High Weibull modulus translates to less material variability in defects, or the defects are more homogeneously distributed, resulting in more predictable probability of failure near a critical stress. Thereby, a material with a high Weibull modulus such as IvoBase tends to be more reliable than a material with a low Weibull modulus such as DENTCA.



	IvoBase	Formlabs	DENTCA	Lucitone
Weibull Modulus	9.5	7.2	3.1	5.8
Characteristic Strength [MPa]	83.7	176.8	147.0	216.5

Discussion

Findings from this study show that amongst the groups tested, Lucitone demonstrated the highest values for flexural strength, strain and porosity. These values were significantly higher than the other brands in the flexural strength and porosity categories. While Lucitone demonstrated a significant difference in percent porosity compared to DENTCA, Formlabs, and IvoBase, all groups had less than .3% averages making the differences in their values clinically insignificant. Collectively the flexural strengths of the 3D printed group were significantly different from the IvoBase group but all groups tested surpassed the minimal required values for denture flexural strength. Lucitone and Formlabs strain values were significantly different from DENTCA and IvoBase but showed no significant difference between themselves.

Characteristic strength is defined as the stress (σ) at which 63.2% of the tested material population has failed. In other words, if 100 samples were broken, 63.2 of them would break at the listed strength value. Weibull modulus describes how defects within a material are distributed throughout the entire material volume. High Weibull modulus translates to less material variability in defects or a more homogeneous distribution of defects. This results in more predictable probability of failure near a critical stress which correlates to a more reliable material. Consequently, a material with a high Weibull modulus, such as IvoBase in this study, tends to demonstrate a more consistent breaking point than a material with a low Weibull modulus such as DENTCA. The high reliability of IvoBase is also reflected in its low standard deviation during flexural strength testing. While IvoBase demonstrated the highest reliability it also had the lowest compressive strength. Lucitone demonstrated the highest characteristic strength, mirroring similar findings as from the three-point flexural test but also showed evidence of unreliability as seen in the low Weibull modulus. When trying to identify a single material that best represents both properties, Formlabs demonstrated relatively high values for both characteristic strength and reliability.

Based on the data obtained, the null hypothesis regarding significant difference in flexural strength between the 3D printed groups and the injection-molded group was rejected as all three 3D printed brands demonstrated significantly higher flexural strengths compared to IvoBase. The null hypothesis in reference to porosity was accepted due to IvoBase showing the same percentage porosity as Formlabs and DENTCA. The null hypothesis regarding variation of flexural strength amongst the 3D printed brands was accepted as there was no significant difference in their average flexural strengths. The null hypothesis regarding differences in percentage porosity was rejected since Lucitone demonstrated a significant difference from the other brands, even though the difference is clinically insignificant.

Small sample size (n = 5) for the porosity test and inadequate cylinder dimensions for testing compressive strength were some of the limitations of this study. Compressive strength was initially part of the research design but the test results were discarded due to unreliable data. After scanning five cylinders per group for porosity on the microCT, ten cylinders from each group were tested for compressive strength on the universal testing machine. The cylinder dimensions were controlled by the microCT machine's limited capacity for securing samples which possibly contributed to unreliable results when testing compressive strength. During both flexural and compressive strength testing some of the samples did not break and the universal testing machining had to be manually stopped. This primarily occurred in the Lucitone and the IvoBase cylinder groups. It was speculated that the small cylinder dimensions may have contributed to this failure to break. The intended sample size for flexural strength was 15 rectangular specimens to ensure sufficient sample power size but additional specimens were manufactured in case any did not meet the quality standard for testing. All the samples printed were of sufficient quality and therefore all were included in the testing. Flexural strength data outliers were also discarded prior to analysis, which further contributed to the uneven sample sizes. Final sample sizes for the flexural strength tests used for data analysis were n=19 for DENTCA, n=17 for Lucitone, n=15 for Formlabs and n=15 for IvoBase.

Recommendations for future studies would be to increase sample size and dimensions (n=10 for porosity tests, n = 15 for compressive strength, and 50 mm diameter x 10 mm) of the cylinders to produce more meaningful data sets and correlations between porosity and compressive strength. In addition, ensuring uniform sample sizes would strengthen the validity of flexural strength findings.

Conclusion

In summary, the 3D printed group outperformed the injection-molded group on flexural strength. Differences in porosity amongst the four tested denture acrylics was insignificant despite Lucitone demonstrating the highest percent porosity. Formlabs demonstrated the best combination of characteristic strength and Weibull modulus while IvoBase proved to be the most reliable.

These results support previous research findings that are trending toward a strong endorsement of CAD/CAM technology as the superior denture fabrication method. Based on these findings, 3D printed dentures provide a reliable alternative to conventional methods and clinical application in removable prosthodontic practices should be genuinely considered. Although these findings are promising, it is recommended that future studies evaluate other interrelated properties of various 3D printed materials such as compressive strength, porosity, and water solubility. As there exists multiple manufacturing options within the larger digital denture category, additional research should be conducted to test physical properties between various milled and printed denture acrylic resins.

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