

CHAPTER 5

DISCUSSION, CONCLUSION AND RECOMMENDATION

5.1 Introduction

This study focused on examining the printability and characterizing 3D-printed denture base resin materials produced through various vat polymerization techniques, namely Stereolithography (SLA), Digital Light Processing (DLP), and Liquid-Crystal Display (LCD). While these techniques operate on the principle of photopolymerization, they differ in their imaging systems and light source, potentially leading to varied printing results. It's worth noting that commercially available 3D printing resins are typically tailored for specific printing methods. For instance, the 3D printing resin (Denture 3D+; NextDent, 3D Systems, The Netherlands) is specifically formulated for use exclusively with the NextDent proprietary 3D printer (Figure 5100, NextDent) due to its close system setup. This signifies that the particular 3D printing resin can only be used on this specific 3D printer, and conversely, the specific printer can only operate with this particular 3D printing resin.

Following a comprehensive characterization process, this study identified notable variations in flexural strength, surface hardness, fracture toughness, degree of conversion, water sorption and solubility, as well as fungal adhesion, depending on the vat polymerization technique employed for fabricating the denture base material. However, the flexural modulus and cell viability showed no significant differences

between the fabrication techniques. Consequently, the null hypothesis of this study was partially rejected.

The study affirms that the 3D printing denture base resin, initially intended for DLP technology, can effectively be utilized in printers employing different vat polymerization techniques, provided that the machine's light source is capable of emitting the required wavelength of light to initiate and activate the polymerization process of the resin material.

5.2 Summary and Discussion of Results

5.2.1 Mechanical Properties

During mastication, the denture base undergoes a combination of compressive and shear stresses in dynamic movement, which can potentially lead to denture failure such as broken denture and fractured teeth. Hence, it is imperative to ensure that the denture possesses adequate mechanical strength to withstand both fracture and deformation under masticatory loads (John et al., 2001). The flexural strength characterizes the denture base material's performance under masticatory loads, while the flexural modulus is linked to its elastic deformation behaviour (B. B. Li et al., 2016).

On the other hand, surface hardness stands as one of the pivotal factors influencing the denture durability. A denture with higher surface hardness exhibits superior resistance against abrasion and indentation during mastication, particularly when dealing with hard substances such as chicken bone (Fouda et al., 2022). Moreover, fracture toughness stands as another critical factor for dentures. It denotes the material's ability to withstand crack propagation, particularly in the presence of a pre-existing

crack or defect. As dentures may develop minor cracks or flaws over time due to regular use, assessing fracture toughness offers insights into their capacity to resist such crack propagation. A denture with high fracture toughness exhibits greater resistance to the spread of these cracks, making it less prone to breakage even in the presence of minor imperfections (Steinmassl et al., 2018).

This study concludes that the SLA technique demonstrated the highest overall mechanical strength. Specifically, in terms of flexural strength, fracture toughness, and surface hardness, the SLA technique yielded outstanding results, surpassing all other tested vat polymerization techniques. This finding aligns with prior research, which indicated that SLA-printed dentures exhibit greater strength compared to those printed using the DLP technique, while the LCD technique demonstrates comparable strength to DLP (Shim, Kim, et al., 2020; Chen et al., 2021; Al-Qarni & Gad, 2022). Nevertheless, the DLP technique yields satisfactory results in terms of mechanical strength, meeting the ISO standards for both flexural strength and modulus. In contrast, the LCD technique exhibits similar flexural strength and modulus and surface hardness to the DLP technique. All the tested mechanical properties followed a consistent trend, whereby the SLA technique exhibited significantly higher strength compared to both the DLP and LCD techniques, while no significant difference was observed between the latter two.

It is important to note that none of the 3D-printed specimens met the minimum criterion of 1.9 MPa/m^2 for fracture toughness as per the ISO standard. However, this criterion is only applicable to commercial denture resins that claim to have enhanced impact resistance, which was not a stated characteristic for the denture base resin used in this study. Subsequently, no minimum requirement was stated in the ISO in regard to

the fracture toughness for unenhanced denture base. A similar outcome was reported in a previous study, where the 3D-printed denture base resin has a lower fracture toughness when compared to the heat-cured resin and fail to meet the ISO recommendation .

Several factors can influence the mechanical strength of 3D-printing resin material, including the degree of conversion (DC), the presence of voids within the material, and the anisotropy of printed objects (S.-H. Kim & Watts, 2008; D. Kim et al., 2020). The rapid layer-by-layer process in additive manufacturing can result in insufficient curing at each layer, leading to reduced overall chain crosslinking. Consequently, some monomers may remain unreacted within the 3D-printed part (Aati, Akram, et al., 2022). To mitigate this issue, post-curing procedure was implemented to promote additional polymerization to the unreacted monomers, thereby enhancing the DC (Perea-Lowery et al., 2021a). The DC represents the percentage of monomers that have been activated and converted into polymers, and it is influenced by factors such as light exposure time, light intensity, and temperature (Bartoloni et al., 2000). In this study, variations in DC may be attributed to differences in exposure to UV light during the printing process since all specimens had a similar print setup and underwent identical post-processing procedures.

In consideration of the mechanical testing results, it's important to acknowledge that the final outcomes and printing time can be influence by the exposure time during the 3D printing process (Madzarević & Ibrić, 2021; Aati, Akram, et al., 2022). Notably, the SLA technique necessitated the lengthiest duration for fabricating the specimens. To produce five flexural test specimens, the DLP, LCD, and SLA groups required 75 minutes, 90 minutes, and 250 minutes, respectively. This disparity arises from the SLA's curing mechanism, which involves the laser progressively curing the photosensitive

resin as it traverses in each cross-sectional layer. In contrast, the LCD and DLP techniques cure the entire cross-sectional layer at once. Despite SLA having a lower light intensity, the prolonged exposure time had led to a higher DC (Reymus et al., 2019). The light intensity and exposure time are directly proportional toward the degree of conversion, a higher light intensity and extended exposure time can induce more monomers to crosslink and polymerized, as a result a higher DC can be achieved (D. Kim et al., 2020; P. Li et al., 2021). However, excessive light intensity or exposure time during the printing process may lead to overcuring the liquid resin in the vat, potentially causing dimensional inaccuracies and a decline in mechanical properties. Thus, a well-balanced combination of light intensity and exposure time is essential to ensure the printed part attains sufficient mechanical properties while still attaining a swift fabrication process with high dimensional accuracy.

As mentioned previously, the LCD and DLP showed no significance difference in terms of mechanical strength. This can be attributed to the compensatory adjustments made for exposure time during the 3D printing process. The light source of the LCD system possessed the lowest light intensity among all groups; to mitigate this weakness, its exposure time of every layer had to be extended. Consequently, the printing rate of the LCD is comparatively lower than the DLP. Although the mechanical strength of the LCD and DLP showed no significant difference, the DLP conferred the advantage of a shorter overall printing duration due to a higher light intensity produced by its light source. In regard of the lower mechanical properties achieved by the DLP compared to the SLA, the DLP proprietary slicer fine-tuned the printing parameters such as light intensity, exposure time, and light off duration to achieve a swifter fabrication period. Essentially, the exposure time was reduced to accelerate the overall printing process, as a result, the mechanical strength was reduced as expected. Nevertheless, all the 3D-

printed denture base resin printed with different vat polymerization techniques still surpass the ISO recommendations for flexural strength and modulus.

5.2.2 Physical Properties

The layer lines on the 3D-printed denture base before sanding and polishing were observed from the optical microscope. These lines are the representation of the stacking of successive layers, with a 45° angle as preset in the printing orientation. No major differences were observed in the surface morphology of the printed specimens. Additionally, after the specimens underwent the sanding and polishing process as mentioned in the post-processing procedure, the layer lines were eliminated from the surface. This indicates that the layering structures or layer lines of the specimens fabricated with vat polymerization techniques only appeared on the external surface, while its core remains solid, proving its isotropic behaviour in mechanical properties.

This aligns with a prior investigation which explored the mechanical properties of the 3D-printed denture bases using different printing orientations (Altarazi et al., 2022). The study found that layered structures were predominantly visible on the exterior surface, while the internal structure remained predominantly solid. Interestingly, significant differences in flexural strength were found between the 0°, 45°, and 90° printing orientations, indicating anisotropic behaviour in mechanical properties (Sun et al., 2021). These findings appeared to conflict with our study. Yet, this discrepancy can be clarified by recognizing that the printing orientation did not influence the material's isotropic behaviour. Instead, it primarily impacted the DC. The 90° orientation involved more successive layers, leading to prolonged exposure to the light source (Altarazi et

al., 2022). Consequently, this increased crosslinking of the monomers, and enhancing the material's mechanical properties.

As dentures are constantly exposed to oral fluids like saliva, water sorption and solubility become the critical factors that could influence their durability and comfortability (Brading Bebington & D Marsh Salisbury, 2003; Altarazi et al., 2022). Water absorption is an inherent property of polymeric materials, owing to their natural polarity (Dhir et al., 2007). The smaller water molecules infiltrate into the polymer network's macrostructure, leading to the degradation of chemical bonds within the resin matrix. This, in turn, affects the polymer's solubility (Zidan et al., 2020). Furthermore, absorbed water can introduce issues such as deformation due to dimensional changes, material degradation and softening, and reduced strength and flexibility (Nguyen et al., 2017). Therefore, it is imperative for the denture base material to exhibit the lowest possible water sorption and solubility.

This study found that the SLA prepared specimens exhibited the lowest sorption rate, primarily attributed to the higher degree of conversion achieved. This higher degree of polymerization resulted in fewer unreacted monomers, leading to reduced water sorption (Gad, Alshehri, et al., 2022). Notably, the results of the sorption test were aligned with the mechanical properties, where the SLA technique demonstrated both the highest strength and the lowest water sorption. When immersing polymeric material in water, unreacted monomers, initiators, and water-soluble elements can leach out from the material itself, this process is referred to as solubility. A previous study highlighted a correlation between water sorption and solubility, indicating that materials with high solubility tend to absorb more water (L. V. J. Lassila & P. K. Vallittu, 2001). This aligns

with our findings, as specimens prepared by the DLP technique exhibited both high water solubility and sorption, respectively.

All the 3D-printed specimens met the ISO requirement for water sorption, which is less than $32 \mu\text{g}/\text{mm}^3$, irrespective of the different tested group. However, none of the groups complied with the standard for solubility, set at $1.6 \mu\text{g}/\text{mm}^3$. This was aligned with a previous study where the 3D-printed specimens fell short of ISO requirements before artificially aged with thermal cycling. However, the water solubility decreased and met the ISO recommendation after aging in tempered water for 24 hours and 5000 thermal cycles (Greil et al., 2023). This may be attributed to the residual monomers leaching out of the material during the aging process, consequently leading to a reduced mass change within the material. In this study, the 3D-printed specimens did not undergo any aging process and were directly commenced with the water immersion test after the post-processing. Hence, the residual monomers within the material could have contributed to the increased water solubility.

During the 3D printing process, the light source of the 3D printer will activate the monomers and photo-initiators in the liquid resin, leading to the transformation of monomers into polymers and the formation of bonded chains at the macromolecular level (Moldovan et al., 2019). Degree of conversion (DC) is the quantification of the ratio of successfully converted monomers to polymers. Consequently, a higher degree of conversion signifies greater intermolecular bonding strength and, by extension, enhanced overall mechanical strength.

In this study, the SLA demonstrated the highest DC among all tested group. Additionally, the mechanical and physical characterization had corresponded to the DC in this finding. whereby the SLA possessed the greatest overall mechanical and physical

properties. This was in line with several previous studies, where a higher DC was associated with higher mechanical, physical, and biological properties (S.-H. Kim & Watts, 2008; Aati et al., 2021; Greil et al., 2023).

In the current study, the printing setup, printing material, post-curing procedure, and post-processing remained strictly consistent across all tested specimens. The only variations were in the printing parameters associated with the vat polymerization techniques for each group. As mentioned above, the extended exposure time in the SLA group had resulted in a higher DC, albeit at the expense of longer printing time. Despite the DLP having the highest light intensity compared to the SLA and LCD groups, the faster fabrication period resulted in lower overall mechanical, physical, and biological properties. Additionally, the method of light projection employed by different vat polymerization could also impact the DC. The SLA technique polymerizes the liquid resin with a high-power UV laser and cures the resin as it travels. On the other hand, in the DLP and LCD techniques, a pixelated pattern is projected directly to the surface of the liquid resin and curing it at once. These differences in the projection method may influence monomer conversion in each and every layer, consequently affecting the overall performance of the printed parts, in terms of mechanical, physical, and biological properties (Lee et al., 2023).

5.2.3 Biological Properties

Biological properties play a crucial role, particularly in the case of dentures. As dentures come into direct contact with oral tissues, they must exhibit biocompatibility, ensuring they do not cause any adverse effects on oral cells (Gautam et al., 2012).

Improperly polymerized acrylate resin can be detrimental to oral tissues, as it may

release unreacted monomers into the oral cavity, leading to inflammation and cell damage (Tzeng et al., 2021). Additionally, reducing fungal adherence and antibacterial properties are an added advantage for the biological aspects of 3D-printed dentures. This is significant because the denture base is susceptible to dental plaque accumulation, often resulting from food debris and inadequate oral hygiene maintenance (Brading Bebington & D Marsh Salisbury, 2003).

In this study, the human gingival fibroblasts (HGFs) were utilized to assess the cytotoxicity effect of the 3D-printed denture base resin. There are two methods of evaluating the cytotoxicity effect of the 3D-printed specimens: extract exposure method and direct contact method. Since the denture comes into direct contact with the oral tissue, this study used the direct contact method to closely simulate the denture environment (Srivastava et al., 2018). After 48 hours of direct contact with the 3D-printed specimens, the cell viability of the HGFs in all tested groups demonstrated a mean value of $\geq 70\%$, indicating that the 3D-printed specimens were not toxic to gingival cells and complied with ISO standards (*ISO 10993-5: 2009 Evaluation of Medical Devices — Part 5: Tests for in Vitro Cytotoxicity*, 2009). It's worth noting that the DLP group demonstrated the lowest cell viability. This observation may be attributed to the testing method. While the direct contact method provides an accurate assessment of cytotoxicity, it may yield a lower cell viability result (Srivastava et al., 2018). This is because, during the direct treatment of HGFs with the 3D-printed specimens, some growing cells may adhere to the surface of the specimens. Subsequently, after the incubation period, the specimens were removed from the 12-well plate, leaving only the adhered cells. This could lead to a lower cell count in the treatment wells compared to the control wells, where no treating specimens were present. Nonetheless, the cell viability result showed no significant difference between

all tested groups, proving the 3D-printed specimens fabricated with different vat polymerization techniques were non-toxic toward the gingival cells.

Additionally, it can be observed that even though significant differences were found in the DC between the tested group, the cell viability did not present any significant differences. This is because through the FTIR analysis, the DC was not directly correlated with the amount of leached unreacted monomers. The FTIR analysis can detect pendant groups that are bounded to the polymeric chains and were not free to leach out (Moldovan et al., 2019). After post-curing the specimens for 30 minutes, as per the manufacturer's instructions, the freely moving monomers had been cured, confirming sufficient post-curing. As a result, no cytotoxic effects were observed in any of the tested groups. Additionally, another explanation could be the unreacted monomers have been released after the specimens were conditioned in distilled water for 24 hours prior to the cell viability test (Aati et al., 2021).

Candida albicans (*C. albicans*) is a major causative agent of denture stomatitis, and inhibiting the growth of this fungal has proven effective in treating and preventing this condition (Hirasawa et al., 2018). This study found that the 3D-printed specimens that fabricated with the SLA technique exhibited the highest adhesion of *C. albicans*. This may be attributed to the specific polymerization mechanism of the SLA technique. Unlike DLP and LCD techniques, where the entire layer was polymerized at once, SLA utilizes a moving laser to cure the liquid resin line by line. This process may result in a more irregular surface on the denture, providing favourable conditions for *C. albicans* adherence. Conversely, the DLP and LCD techniques, with their imaging system that cures the entire layer simultaneously, demonstrated better performance in inhibiting *C. albicans* adherence on the specimens' surface. Although the surface morphology of the

specimens showed no significant differences after sufficient sanding and polishing, the corners and small surface circumference area of the specimens may present a rougher surface. This is because the edges and side surfaces of the specimens were hard to reach and may not receive an even and throughout sanding and polishing. In addition to the specific polymerization mechanism of the SLA technique, it was suspected that the irregular surface may be also presented on the side surface of the specimens and didn't receive sufficient polishing.

An earlier study examined the surface roughness of denture material exhibited by two DLP techniques and conventional heat-polymerized material (Al-Dulaijan et al., 2022). It revealed that surface roughness exhibited no significant differences across the two DLP techniques, even with different printing orientations and applying varied post-curing durations. This finding aligns, to some extent, with the results of our current study. Both LCD and DLP employ a similar mechanism, wherein the cross-sectional layer is cured at once, resulting in comparable surface roughness. Conversely, the SLA technique, with its method of curing the cross-sectional layer line by line, led to higher surface roughness. In addition, this corresponds with another study that compared the surface roughness of DLP and SLA-printed dental splints, finding that the DLP-printed specimens exhibited lower roughness (Barone et al., 2019). However, as indicated in a previous study, the layered structures inherent from the additive manufacturing can be mitigated through thorough mechanical polishing (Altarazi et al., 2022). Hence, any irregular surface texture could be rectified with sufficient post-mechanical finishing and polishing. In the current study, it was observed that the surface morphology of the 3D-printed specimens achieved a smooth surface after sanding and polishing, effectively eliminating the layered structure. Nevertheless, significant differences were still found in the adherence of *C. albicans* between the tested group. This may be attributed to the

curved surface of the designed specimens, which presented a challenge for thorough sanding. Given their cylindrical shape, the outer curvature of the cylinder posed difficulty in achieving complete sanding and polishing. Consequently, layered structures and minor voids may still have been present in the 3D-printed specimens, potentially accounting for the differences in *C. albicans* adherence.

Furthermore, the findings of this current study aligned with another prior investigation comparing *C. albicans* adhesion on conventional heat-cured, subtractive milled, and 3D-printed denture base (Jung, 2020). The results indicated that the DLP-printed specimens exhibited relatively lower *C. albicans* adherence compared to the SLA-printed specimens. However, due to the limited sample size, the differences were statistically insignificant. Additionally, other studies have discovered significant differences between the microbial adhesion and printing orientation. The microbial adhesion with higher printing orientations, indicating that an increase in layers led to increased microbial adhesion (Shim, Kim, et al., 2020; Yacob et al., 2023). However, the surface of the testing specimens of these studies didn't not undergo mechanical sanding and polishing. This explained the increased microbial adhesion, as the layering structures on the surface of the specimens were not removed and resulted in a higher surface roughness that promote the microbial adhesion. It's worth noting that the adherence results of the current study were contradicting with another study that concluded that no significant differences were found on the adherence of the *C. albicans* when using DLP and SLA techniques (P. Li et al., 2022). This is due to fungal adhesion on denture base material can vary significantly due to numerous factors, including fungus concentration in the testing environment, experimental setups, variation of resin materials, and post-processing procedures (Koujan et al., 2022; P. Li et al., 2022). Therefore, contradicting results can be expected when compared to the previous studies.

5.3 Implication and Recommendations of the Study

Digital technology has undergone exponential advancement in recent years, with 3D printing making significant inroads in the dental field. Currently, vat polymerization stands as the most widely utilized 3D printing technology in dentistry. Understanding the full potential and assessing the feasibility and reliability of this technology can greatly enhance its application across various industries, particularly in dentistry.

This study exemplifies the versatility of materials that can be employed within different vat polymerization techniques by employing the 3D-printing denture base resin (Denture 3D+; NextDent, 3D Systems, The Netherlands), an acrylic-base resin specifically designed for DLP technique in SLA and LCD systems. Furthermore, this study investigated the denture material fabricated with three common vat polymerization techniques to examine their differences in terms of mechanical, physical, and biological properties.

It's important to note that this study only examined a single type of 3D printing denture base resin. This particular resin holds the distinction of being the first and only registered 3D printing denture base resin in Malaysia with CE, Standard and Industrial Research Institute of Malaysia (SIRIM), and Food and Drug Administration (FDA) approval. Results may vary with different brands and types of 3D printing resins. Thus, future research could incorporate diverse 3D printing resins, along with additional characterizations including surface roughness and colour stability. Additionally, high-performance liquid chromatography (HPLC) can be used to analyse the monomer elution within the 3D-printed specimens.

5.4 Conclusions

Within the limitations of this study, it can be concluded that, the 3D printing resin designed for DLP printers can be effectively used with different vat polymerization techniques provided the appropriate wavelength of light is available in the 3D printer buildup. Furthermore, the SLA technique exhibited outstanding performance in mechanical properties, demonstrating the highest flexural strength, surface hardness, and fracture toughness, as well as the lowest water sorption and solubility, attributed to its higher degree of conversion. Nevertheless, that this comes at the expense of a slower printing rate and higher fungal adhesion. In contrast, although the LCD technique did not yield remarkable results, it still met the acceptable standards outlined by the ISO. In summary, the LCD technique can achieve similar results with the DLP technique in terms of physicomaterial and biological properties. While the LCD technique may have a slower printing rate, it is generally considered to be more system-friendly and easier to manipulate compared to the DLP and SLA techniques.