CAD-CAM complete denture resins: an evaluation of biocompatibility, mechanical properties, and surface characteristics

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Abstract: Objectives This study evaluated the biocompatibility, mechanical properties, and surface roughness of CAD-CAM milled and rapidly-prototyped/3D-printed resins used for manufacturing complete dentures. Methods Six groups of resin specimens were prepared, milled-base (MB), milled-tooth shade (MT), printed-tooth shade (PT), printed-base with manufacturer-recommended 3D-printer (PB1), printed-base with third-party 3D-printer (PB2), printed-base in a vertical orientation (PB2V). Human epithelial (A-431) and gingival (HGF-1) cells were cultured and tested for biocompatibility using Resazurin assays. Three-point bending and nanoindentation tests measured the mechanical properties of the resin groups. Surface roughness was evaluated using a high-resolution laser profilometer. ANOVA and post-hoc tests were used for statistical analyses (\( \alpha = 0.05 \)). Results: There were no significant differences in biocompatibility between any of the investigated groups. MB revealed a higher ultimate strength (\( p = 0.008 \)), elastic modulus (\( p = 0.002 \)), and toughness (\( p = 0.014 \)) than PB1. MT had significantly higher elastic modulus than PT (\( p < 0.001 \)). Rapidly-prototyped resin samples with a manufacturer-recommended 3D-printer (PB1) demonstrated higher ultimate strength (\( p = 0.008 \)), elastic modulus (\( p < 0.001 \)), hardness (\( p < 0.001 \)) and a reduced surface roughness (\( p < 0.05 \)) when compared with rapidly-prototyped groups using a third-party 3D-printer (PB2). Rapidly-prototyped samples manufactured with a vertical printing orientation (PB2V) revealed a significantly lower elastic modulus than samples groups manufactured using horizontal printing orientation (PB2) (\( p = 0.011 \)). Conclusions: Within the limits of this present study, CAD-CAM milled and rapidly-prototyped complete denture resins performed similarly in terms of biocompatibility and surface roughness. However, the milled denture resins were superior to the rapidly-prototyped denture resins with regard to their mechanical properties. Printing orientation and type of 3D-printer can affect the resin strength and surface roughness.

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CAD-CAM complete denture resins: an evaluation of biocompatibility, mechanical properties, and surface characteristics

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ABSTRACT

Objectives: This study evaluated the biocompatibility, mechanical properties, and surface roughness of CAD-CAM milled and rapidly-prototyped/3D-printed resins used for manufacturing complete dentures.

Methods: Six groups of resin specimens were prepared, milled-base (MB), milled-tooth shade (MT), printed-tooth shade (PT), printed-base with manufacturer-recommended 3D-printer (PB1), printed-base with third-party 3D-printer (PB2), printed-base in a vertical orientation (PB2V). Human epithelial (A-431) and gingival (HGF-1) cells were cultured and tested for biocompatibility using Resazurin assays. Three-point bending and nanoindentation tests measured the mechanical properties of the resin groups. Surface roughness was evaluated using a high-resolution laser profilometer. ANOVA and post-hoc tests were used for statistical analyses (α = 0.05).

Results: There were no significant differences in biocompatibility between any of the investigated groups. MB revealed a higher ultimate strength (p = 0.008), elastic modulus (p = 0.002), and toughness (p = 0.014) than PB1. MT had significantly higher elastic modulus than PT (p < 0.001). Rapidly-prototyped resin samples with a manufacturer-recommended 3D-printer (PB1) demonstrated higher ultimate strength (p = 0.008), elastic modulus (p < 0.001), hardness (p < 0.001) and a reduced surface roughness (p < 0.05) when compared with rapidly-prototyped groups using a third-party 3D-printer (PB2). Rapidly-prototyped samples manufactured with a vertical printing orientation (PB2V) revealed a significantly lower elastic modulus than samples groups manufactured using horizontal printing orientation (PB2) (p = 0.011).

Conclusions: Within the limits of this present study, CAD-CAM milled and rapidly-prototyped complete denture resins performed similarly in terms of biocompatibility and surface roughness. However, the milled denture resins were superior to the rapidly-prototyped denture resins with regard to their mechanical properties. Printing orientation and type of 3D-printer can affect the resin strength and surface roughness.

Clinical significance

Appropriate CAD-CAM manufacturing technique should be considered whilst manufacturing removable complete dentures (CDs) as the mechanical properties and surface roughness may vary. When fabricating CDs with the rapid-prototyping technique, it is important to employ the correct printing orientation, and a 3D-printer that is recommended by the resin manufacturer.

1. Introduction

For over half a century, the conventional flask-pack-press or compression molding method has been used to fabricate removable complete dentures (CDs). Traditionally, CDs have been processed using polymethylmethacrylate (PMMA) resin with heat polymerization [1]. This method has evolved over the years in response to advancements in
the PMMA resin’s properties and associated processing protocols, including the use of auto-polymerizing, microwave-processing, or injection-molding techniques [2]. The principle has remained essentially unchanged. PMMA resin is shaped into the desired mold under pressure and polymerized. However, this protocol has undergone a remarkable transformation in the recent years following the introduction of computer-aided design and computer-aided manufacturing (CAD-CAM) procedures for CDs.

The fabrication of CDs using CAD-CAM techniques was first published in the 1990s [3] and has increased dramatically over the last decade [4]. This technology-driven manufacturing process owes its rapid development to several critical factors, including, but not limited to, shifting of the clinicians’ and dental technicians’ behaviors, the use of improved materials along with a possible decrease in the clinical chairside time, total patient visits, and dental laboratory costs [5–7]. Evidence in literature reveal a clear preference for CAD-CAM fabricated CDs by both patients and clinicians [8, 9]. Furthermore, evidence in literature also suggest that in terms of the trueness of the intaglio surfaces, CAD-CAM fabricated CDs were not inferior to conventionally manufactured CDs [10–13].

Two manufacturing processes exist for fabricating CDs: a subtractive, and an additive technique. The subtractive or CAD-CAM milling process entails milling the CD out of a commercially manufactured PMMA disc that has been pre-polymerized. Due to the fact that this disc is manufactured under high pressure and well-controlled conditions, many studies have demonstrated that milled resins show superior mechanical and surface properties [14–16], comparable color stability [17–19], reduction of microbial colonization [20, 21] and a lower leech rate of residual monomer [22], compared to compression molding resins. On the other hand, the additive manufacturing process, also known as rapid-prototyping or 3D-printing, involves serial apposition of the liquid resin material on a support structure followed by curing by visible light, ultraviolet light, heat, or laser [23]. This layering and curing process is replicated until the CD form specified in the CAD is achieved.

CAD-CAM rapid-prototyping process is being increasingly used in the dental field, for manufacturing fixed prostheses, surgical templates, occlusal splints, and even CDs [23, 24]. However, there are only a few publications that report on the mechanical properties and surface characteristics of CAD-CAM rapidly prototyped resins used for fabricating CDs [25, 26]. Furthermore, there is a paucity of studies comparing the differences in biocompatibility between CAD-CAM milled and rapidly-prototyped CDs. Therefore, this study was undertaken to evaluate the differences in the biocompatibility, mechanical properties, and surface roughness of resins used to manufacture CAD-CAM milled and rapidly-prototyped CDs. The study further evaluated the influence of different printers and the printing orientation on the mechanical properties of rapidly-prototyped resins. The primary null hypothesis set for this study was that there would be no difference in the biocompatibility, mechanical properties, or surface roughness between CAD-CAM milled and rapidly-prototyped resins used to manufacture CAD-CAM CDs. The secondary null hypothesis set for this study was that there would be no influence of different 3D-printers or the printing orientation on the mechanical and surface properties of rapidly-prototyped resins that are used for the fabrication of CAD-CAM CDs.

2. Materials and methods

2.1. Study design

Custom specimens were manufactured using resins employed for the fabrication of CAD-CAM subtractively, and additively manufactured CDs and were distributed into various study groups, as shown in Table 1. Resin specimens were fabricated with dimensions and in specific numbers for the various tests, (biocompatibility assays: n = 9 per study group, dimension = 10 × 10 × 2 mm; three-point bending test: n = 5 per study group, dimension = 65 × 10 × 3 mm; nanoindentation test: n = 5 per study group, dimension = 11 × 11 × 2 mm; surface roughness test n = 5 per study group, dimension = 20 × 20 × 1.5 mm) as shown in Appendix 1.

Pre-polymerized PMMA discs with a base pink (AvaDent Denture base puck, AvaDent, Global Dental Science Europe, Tilburg, The Netherlands) and a toothshade (Avadent Extreme CAD CAM shaded puck YW10, AvaDent, Global Dental Science Europe, Tilburg, The Netherlands) were used for manufacturing the resin specimens for milled group. The discs were sliced using a rotary table saw (Inca, Injecta, Teufenthal, Switzerland) equipped with a 3 mm thick stainless circular blade (Oerlikon Werkzeuge, Hör, Switzerland) and reduced to the required dimensions manually.

Rapidly-prototyped specimens with a manufacturer-recommended 3D-printer (Rapid Shape D30, Rapid Shape GmbH, Heimsheim, Germany) were manufactured using a base pink (NextDent Base, Vertex-Dental B.V., Soesterberg, The Netherlands) and a toothshade (NextDent C&B, Vertex-Dental B.V., Soesterberg, The Netherlands) resins for 3D-printing. The samples were printed in a horizontal orientation with a layer thickness of 100 mm per layer. The printed samples were rinsed twice in a 96% ethanol solution in an ultrasonic bath to remove excess material. A first rinse of 3 min was followed by a second rinse in a clean 96% ethanol solution for approximately 2 min. The printed samples were then cleaned, dried, and placed in an ultraviolet light box (LC-3DPrint Box, NextDent B.V., Soesterberg, The Netherlands) for 10 min for additional polymerization. The light box had 4 Dulux Blue UV-A lamps and four 18W/71 lamps (Dulux L blue) delivering a wavelength of blue UV-A 315 to 400 nm and an output of 43.2 kJ.

Rapidly-prototyped specimens using a third-party 3D-printer (Form 2, Formlabs, Massachusetts, USA) were manufactured in the same way as the manufacturer-recommended 3D-printer group with only a pink base resin (NextDent Base, Vertex-Dental B.V., Soesterberg, The Netherlands). Further rapidly-prototyped specimens were manufactured employing a vertical orientation, using a manufacturer-recommended 3D-printer (Rapid Shape D30, Rapid Shape GmbH, Heimsheim,
Germany) and a pink base resin (NextDent Base, Vertex-Dental B.V., Soesterberg, The Netherlands). After controlling the required dimensions, all specimens were polished manually by a master dental technician as described in our previous published study [27].

After the final polishing, the resin samples were disinfected for culture and mechanical testing. The specimens were first rinsed with normal saline before immersion in a 70% ethanol solution for 30 min, then rinsed again in normal saline twice and then dried with sterile cotton. They were sterilized for 15 min under ultra-violet light with a wavelength of 254 nm emitted by a 15-watt UV lamp present in the safety cabinet (SafeFAST premium 212, LogicAir, Saint-Aubin, Switzerland).

2.2. Biocompatibility assays

2.2.1. Cells

Two cell lines frequently used in models assessing biocompatibility within the gingival area were used separately in a series of three separate experiments ran in triplicate: human epithelial cells (A-431 ATCC® CRL-1555™, epidermoid cell line, squamous carcinoma) and human gingival cells (HGF-1 ATCC® CRL-2014™, normal primary cells). Cells were cultured in Dulbecco’s Modified Eagle’s Medium (DMEM medium, Life Technologies, Carlsbad, CA, USA) supplemented with 10% fetal calf serum (Eurobio, Les Ulis, France), 1% Penicillin/Streptomycin/Fungizone (Life technologies) and 2% HEPES (Life technologies). They were used at passages 3–5 for proliferation assays. Four groups of resin samples (n = 9 per study group) were placed in 24-well plates (TPP techno Plastic Products, Trasadingen, Switzerland), and cells were seeded at a density of 2600/cm². As control of normal cell growth, cells were seeded directly on culture dish polystyrene. On days 4, 7, 14, and 21, resazurin assays were performed as described before [28, 29].

2.2.2. Cell culture and proliferation (Resazurin assay)

The A-431 and HGF-1 cells were cultured on MB, MT, PT, and PB1 substrates plates. For each cell line (A-431 and HGF-1) and each resin specimen group, cells were cultured for 21 days in triplicate. This assay was repeated three times (n = 9) for the two cell lines separately, as described in earlier publications [29]. Resazurin assays were done on days 4, 7, 14, and 21 within each test run. Once the cultures were ready, on the day of measurement, resazurin (Resazurin Sodium salt, Sigma Aldrich, St. Louis, MO, USA) with a concentration of 10 μg/ml was added in the culture media to measure the proliferation of the cells. The cells were maintained at 37 °C and 5% CO₂ for 4 h. Resazurin is transformed to resofurin during this incubation. The absorbance of resofurin in culture media was assessed at 570 and 630 nm. The percentage of reduction of the resazurin was then calculated according to the manufacturer’s instructions and used for data analysis.

2.3. Mechanical properties and surface characteristics

2.3.1. Three-point bending test

Three-point bending tests evaluated the mechanical properties of the resin samples from the six groups (MB, MT, PT, PB1, PB2, and PB2V). The resin samples were stored in water at 37 °C for 24 h. The span length of the specimen was 50 mm, and a vertical load was applied at the midpoint of the specimen at a crosshead speed of 1 mm/min by a universal testing machine (AG-X Plus, Shimadzu Corporation). The ultimate strength, flexural elastic modulus, stress at the proportional limit (yield point), flexural strain at the proportional limit, and toughness were determined.

2.3.2. Nanoindentation test

A nanoindenter equipped with a Berkovich indenter (CSM Instrument, Peseux, Switzerland) was used to perform the tests on resin samples from five groups (MB, MT, PT, PB1, and PB2). The Berkovich diamond tip was calibrated using a fused silica standard provided by the manufacturer. A load of 8 mN was applied at a rate of 76 mN•min⁻¹. At maximum constant load, a 10-s holding period was imposed. The applied load and penetration depth were continuously recorded during the loading and unloading cycle. Five indentations were placed for each
2.4. Laser profilometry

Resin samples from five groups were measured and the corresponding profiles were generated. Surface roughness profile (R) was measured using a high-resolution white light non-contact laser profiler (CyberSCAN CT 100, Cyber technologies, Eching-Dietersheim, Germany) with a z-resolution of 20 nm and a lateral resolution of 1 μm. R was calculated using a Gaussian profile filter with the cut-off wavelength (λc) set to 0.8 mm and the sampling length to 4 mm, in each total scanning length of 5.6 mm as per the specifications by the International Standards Organization (ISO 11,562). This total scanning length is then split into five sampling lengths. R is analyzed within this total scanning length, and the commonly measured roughness characteristics, average roughness (R_a) and maximum roughness (R_max), were analyzed. R_z is the arithmetic mean value of all heights (peaks and valleys) in the given roughness profile. R_m is the maximum of all roughness depths (distance between the deepest valley and the highest peak) measured within the complete scan length. Another parameter from the surface roughness profile (R) is the mean height of profile elements (R_m), representing the average value of the height of the curve element along the sampling length.

2.5. Statistical analysis

Data collected were verified for normal distribution using the Kolmogorov-Smirnov test and compared for statistical significance using two-way ANOVA and post hoc test (Tukey’s HSD test). The level of statistical significance for all tests was at p < 0.05. Statistical analyses were performed using a statistical software (Ver 25.0, IBM SPSS Statistics, IBM, NY, USA).

3. Results

3.1. Biocompatibility assays

Both epithelial cells (A-431) and gingival cells (HGF-1) grew gradually around 3 to 4-fold increase from day 4 to day 21, which is the same trend as the control group on plastic (Fig. 1). For A-431 from day 4 to day 21, MB showed a 3.9-fold increase, MT showed a 4.0-fold increase, PT showed a 3.5-fold increase, and PB1 showed a 3.5-fold increase. For HGF-1 from day 4 to day 21, MB showed a 2.9-fold increase, MT showed a 3.5-fold increase, PT showed a 3.4-fold increase, and PB1 showed a 2.8-fold increase. However, the two-way ANOVA results from Table 2 show that there was no statistical difference among the different resin groups (MB, MT, PT, and PB1) from day 4 to day 21 for either A-431 (F (312) = 0.500, p = 0.6829) and HGF-1 (F(312) = 2.035, p = 0.1123).

3.2. Mechanical properties

Milled resins demonstrated a higher ultimate strength than the printed resins, the resins printed with manufacturer-recommended 3D-
printer revealed higher ultimate strength than the resins printed with a third-party 3D-printer and those printed with a vertical orientation (Fig. 2A). Post-hoc comparisons in Table 3 show that MB had superior ultimate strength than PB1 \((p = 0.0083)\), MT had superior ultimate strength than PB1 \((p = 0.0071)\), and PB1 had superior ultimate strength than PB2. However, there was no statistical significance between MB-MT, MB-PT, MT-PT, PT-PB1, and PB2-PB2V.

Milled resins also demonstrated a higher elastic modulus than the printed resins; the resins printed with the manufacturer-recommended 3D-printer showed higher elastic modulus than the resins printed with a third-party 3D-printer and the resins printed with a vertical orientation. Post-hoc comparisons in Table 3 show that MB had superior elastic modulus than PT \((p = 0.0001)\), MT had superior elastic modulus than PB1 \((p = 0.0025)\), MT had superior elastic modulus than PT \((p < 0.0001)\), MT had superior elastic modulus than PB1 \((p = 0.0010)\), PB1 had superior elastic modulus than PB2 \((p < 0.0001)\), and PB2 had superior elastic modulus than PB2V \((p = 0.0112)\). However, there was no statistical significance between MB-MT and PT-PB1 (Fig. 2B).

Milled resins demonstrated higher toughness than the printed resins, the resins printed with the recommended 3D-printer showed identical toughness as the resins printed with a third-party 3D-printer and the resins printed with a vertical orientation (Fig. 3A). Post-hoc comparisons in Table 3 show that MB had superior toughness than PB1 \((p = 0.0137)\). However, there was no statistical significance between MB-MT, MB-PT, MT-PT, MT-PB1, PT-PB1, PB1-PB2, and PB2-PB2V.

The milled resins showed similar yield point as the printed resins, resins printed with the recommended 3D-printer had the same yield point as the resins printed with a third-party 3D-printer and the resins printed with a vertical orientation (Fig. 3B). Additionally, post-hoc comparisons in Table 3 show no statistically significant difference between MB-MT, MB-PT, MB-PB1, MT-PT, MT-PB1, PT-PB1, PB1-PB2, and PB2-PB2V.

Milled resins had the same strain at yield point as the printed resins, resins printed with the recommended 3D-printer had the same strain at yield point as the resins printed with a third-party 3D-printer and the resins printed with a vertical orientation (Fig. 4A). Additionally, post-hoc comparisons in Table 3 revealed no statistically significant difference between MB-MT, MB-PT, MB-PB1, MT-PT, MT-PB1, PT-PB1, PB1-PB2, and PB2-PB2V.

Milled resins had the same hardness as the printed resins, the resins printed with the recommended 3D-printer showed higher hardness than the resins printed with a third-party 3D-printer. Post-hoc comparisons in Table 3 show that PB1 had superior hardness than PB2 \((p < 0.0001)\; (Fig. 4B). There was no statistically significant difference between MB-MT, MB-PT, MB-PB1, MT-PT, PB1-PB2, and PT-PB1.

### 3.3. Surface roughness

Fig. 5 illustrates the typical profilometer scans of the various study groups. There was no difference between the surface roughness of the milled and the 3D-printed resins. Resin groups fabricated with the recommended 3D-printer were smoother than the resins printed with a third-party 3D-printer. Post-hoc comparisons show that PB1 had a smoother surface than PB2 \((R_a \leq 0.0085; R_z \leq 0.0152; R_z \leq 0.0051; \text{Table 2; Figs. 6A, 6B})\). However, there was no statistically significant difference between MB-MT, MB-PT, MB-PB1, MT-PT, MT-PB1, and PT-PB1.

### 4. Discussion

Biocompatibility is a critical consideration for the clinical use of dental materials. Adverse reactions of the oral mucosa in direct contact with the introduced foreign materials might result in pain, hypersensitivity, and even allergies or burning mouth sensations [31, 32]. As a result, biocompatibility testing must be used to ensure patient safety. The cell lines utilized in the biocompatibility experiments (human epithelial cell (A-431) and human gingival cell (HGF-1)) are

![Fig. 2](image_url) Ultimate strength (A) and Elastic modulus (B) [MB-milled base, MT-Milled tooth shade, PT-Rapidly-prototyped/3D-printed tooth shade (printing orientation: horizontal), PB1-Rapidly-prototyped/3D-printed base with a manufacturer-recommended 3D-printer (printing orientation: horizontal); PB2-Rapidly-prototyped/3D-printed base with a third-party 3D-printer (printing orientation: horizontal); PB2V-Rapidly-prototyped/3D-printed base with a third-party 3D-printer (printing orientation vertical); p-value: Tukey’s HSD (significance: \(p<0.05\)).]
Fig. 3. Toughness (A) and Yield point (B) [MB-milled base, MT-Milled tooth shade, PT- Rapidly-prototyped/3D-printed tooth shade (printing orientation: horizontal), PB1- Rapidly-prototyped/3D-printed base with a manufacturer-recommended 3D-printer (printing orientation: horizontal); PB2- Rapidly-prototyped/3D-printed base with a third-party 3D-printer (printing orientation: horizontal), PB2V- Rapidly-prototyped/3D-printed base with a third-party 3D-printer (printing orientation vertical); p-value: Tukey’s HSD (significance: $p < 0.05$)].

Fig. 4. Strain at yield point (A) and hardness (B) [MB-milled base, MT-Milled tooth shade, PT- Rapidly-prototyped/3D-printed tooth shade (printing orientation: horizontal), PB1- Rapidly-prototyped/3D-printed base with a manufacturer-recommended 3D-printer (printing orientation: horizontal); PB2- Rapidly-prototyped/3D-printed base with a third-party 3D-printer (printing orientation: horizontal), PB2V- Rapidly-prototyped/3D-printed base with a third-party 3D-printer (printing orientation vertical); p-value: Tukey’s HSD (significance: $p < 0.05$)].
well-established and used in the laboratory to evaluate the biocompatibility of materials [33, 34]. Biocompatibility experiments demonstrated that both types of cells, A-431 and HGF-1, proliferated on both types of resin substrates, milled and printed. The results demonstrated a healthy proliferation of A-431 on both resin substrate groups, but no statistically significant difference was observed. The HGF-1 cell assay exhibited a similar trend to the A-431 assay with no statistically significant difference. Thus, based on the results of our current investigation, the null
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Table 3
Mechanical properties and surface roughness of the different CAD-CAM milled and rapidly-prototyped resin groups.

| Resin Groups | Ultimate Strength [MPa] (mean ± SD) | Elastic Modulus [GPa] (mean ± SD) | Toughness [N. mm] (mean ± SD) | Yield Point [MPa] (mean ± SD) | Strain at Yield Point [mm] (mean ± SD) | Hardness [VHN] (mean ± SD) | Rₐ [µm] (mean ± SD) | Rₛ [µm] (mean ± SD) | Rₜ [µm] (mean ± SD) |
|--------------|------------------------------------|----------------------------------|------------------------------|-------------------------------|----------------------------------------|-----------------------------|-------------------|-------------------|-------------------|
| MB (n = 5)   | 114.108 ± 3.03                     | 3.038 ± 0.08                     | 794.322 ± 65.17              | 8.134 ± 3.05                  | 0.271 ± 0.11                           | 15.940 ± 0.36              | 0.086 ± 0.37      | 0.556 ± 1.035     | 1.038 ± 1.035     |
| MT (n = 5)   | 114.508 ± 4.63                     | 3.064 ± 0.05                     | 678.984 ± 127.72             | 5.538 ± 0.87                  | 0.175 ± 0.03                           | 18.440 ± 0.99              | 0.078 ± 0.02      | 0.446 ± 0.888     | 0.28              |
| PT (n = 5)   | 99.684 ± 1.61                      | 2.624 ± 0.04                     | 586.086 ± 105.69             | 5.658 ± 1.21                  | 0.205 ± 0.05                           | 18.540 ± 1.31              | 0.088 ± 0.02      | 0.498 ± 0.950     | 0.16              |
| PB1 (n = 5)  | 90.756 ± 16.29                     | 2.716 ± 0.14                     | 408.038 ± 262.94             | 5.818 ± 1.73                  | 0.212 ± 0.06                           | 17.000 ± 1.26              | 0.118 ± 0.05      | 0.616 ± 1.104     | 0.29              |
| PB2 (n = 5)  | 67.348 ± 11.39                     | 2.108 ± 0.04                     | 271.334 ± 192.55             | 4.346 ± 0.11                  | 0.203 ± 0.01                           | 6.680 ± 2.26               | 0.426 ± 0.28      | 1.804 ± 3.084     | 1.64              |
| PB2V (n = 5) | 71.512 ± 10.77                     | 1.832 ± 0.22                     | 414.050 ± 161.85             | 4.16 ± 0.07                   | 0.211 ± 0.06                           |                         |                  |                   |                   |

ANOVA(p-value)

| Post-hoc comparisons (p-value) | Ultimate Strength | Elastic Modulus | Toughness | Yield Point | Strain at Yield Point | Hardness |
|-------------------------------|-------------------|-----------------|-----------|-------------|-----------------------|----------|
| MB vs. MT                     | <0.001            | <0.001          | <0.001    | <0.001      | <0.001                | <0.001   |
| MB vs. PT                     | 1.000             | 0.999           | 0.879     | 0.126       | 0.108                 | 0.065    |
| MB vs. PB1                    | 0.198             | <0.001          | 0.384     | 0.158       | 0.440                 | 0.052    |
| MB vs. PB1                    | 0.008             | 0.002           | 0.014     | 0.212       | 0.561                 | 0.744    |
| MT vs. PT                     | 0.176             | <0.001          | 0.947     | 1.000       | 0.956                 | 1.000    |
| MT vs. PB1                    | 0.007             | 0.001           | 0.144     | 1.000       | 0.898                 | 0.486    |
| PT vs. PB1                    | 0.678             | 0.808           | 0.551     | 1.000       | 1.000                 | 0.421    |
| PB1 vs. PB2                   | 0.008             | 0.000           | 0.784     | 1.000       | 1.000                 | 0.008    |
| PB2 vs. PB2V                  | 0.981             | 0.911           | 0.753     | 1.000       | 1.000                 | 0.000    |

MPa, Megapascal; SD, standard deviation; GPa, Gigapascal; N.mm, Newton millimeter; VHN, Vickers hardness number; µm, micrometer; *, p-value: Tukey’s HSD test, α = 0.05, this table contains only selected representative post-hoc comparisons; MB, Milled Base; MT, Milled Tooth-shade; PB1, Printed Base with recommended 3D-printer; PB2, Printed Base with third-party 3D printer; PB2V, Printed Base with vertical orientation; PT, Printed Tooth-shade; Surface roughness: Rₚ, Average roughness; Rₛ, Average peak to valley height; Rₜ, Maximum height of profile; SD, Standard deviation.

hypothesis regarding biocompatibility cannot be rejected.

Even if both milling and rapid prototyping processes utilize a digital 3D-image file created with CAD software to fabricate CDs, the two manufacturing approaches are radically different. Each approach has its own advantages and disadvantages. CDs manufactured from pre-polymerized PMMA disc should theoretically exhibit no shrinkage and porosity associated failures that are usually encountered with the packing and polymerization processes because the discs are manufactured under high pressure and optimal temperature. Additionally, these milled CDs should release less monomer and exhibit improved mechanical and surface properties. Concerning the trueness of the intaglio surfaces, milling techniques are limited due to the size of the milling instrument, hence the surface might show a relatively large variability [12]. Intuitively, one might assume that the trueness of printed resins, that are sprayed in their liquid form into the desired mold may result in a better fit, but at present, the evidence is not conclusive. However, the fact that the polymerization process takes place after shaping the material might also be a disadvantage in terms of trueness, as the associated volumetric shrinkage might lift off the palatal plate, hence compromising the upper CD’s suction effect in a clinical context. This phenomenon also occurs in traditional heat-polymerized pack and flask CDs and can effectively be compensated by saving a post-dam on the denture. Since in milling techniques the polymerization process takes place before shaping the final CD, future research should investigate if milled CDs still need the same grading of a post-dam to achieve suction.

The rapid prototyping technique utilizes unpolymerized liquid resins to fabricate CDs, and once processed, the method requires an additional final light polymerization step. Polymerization shrinkage and compromised mechanical properties are potentially conceivable during the rapid prototyping workflow, as the complete dentures are not fully polymerized before the final light-polymerization step. When removing the partially polymerized complete denture from the construction platform, deformation of the prostheses may occur. Additionally, a residual coating of unpolymerized resin is invariably present on the completed prostheses and must be removed thoroughly with a suitable solvent. The additive manufacturing process is said to have several advantages, including increased accuracy, reduced material waste, and minimal infrastructure costs. However, many studies indicate that rapidly prototyped CDs show lower trueness of fit than milled CDs [10, 35–38]. The reduced material waste and cheap infrastructure costs have not yet been adequately validated. Nonetheless, tabletop 3D printers are less expensive and easier to transport than milling machines, making them more affordable to private clinics and dental laboratories, as well as to low-income countries where edentulism is prominent and skilled dental laboratory personnel are limited. Additionally, on-site manufacturing would eliminate delivery delays and save shipping costs.

In terms of mechanical properties, the current study revealed that milled resins had significantly superior ultimate strength, elastic modulus, and toughness than rapidly prototyped resins, while there was no significance regarding yield point, strain at yield point, and hardness. Hence, the null hypothesis regarding the difference in the mechanical properties between the milled and rapidly-prototyped resins can be partially rejected. Furthermore, the current study evinced that rapidly-prototyped resins with the recommended 3D-printer (Rapid Shape D30, Rapid Shape GmbH, Heimsheim, Germany) showed significantly higher ultimate strength, elastic modulus, and hardness than rapidly-prototyped resins with third-party 3D-printer (Form 2, Formlabs, Massachusetts, USA). Also, printing in a vertical orientation revealed a significantly lower elastic modulus. As a result, the null hypothesis regarding the influence of 3D-printer and the printing orientation on the mechanical properties is rejected. Numerous studies have demonstrated that printing angulation and the layer thickness affect the trueness of rapidly prototyped CDs [24, 37, 39–41] but no studies exist that have yet been adequately validated. Nonetheless, tabletop 3D printers are less expensive and easier to transport than milling machines, making them more affordable to private clinics and dental laboratories, as well as to low-income countries where edentulism is prominent and skilled dental laboratory personnel are limited. Additionally, on-site manufacturing would eliminate delivery delays and save shipping costs.

The surface roughness could be one of the factors that contribute to microbial colonization on the denture surfaces [20, 21] and the color
stability of the denture materials [17–19]. The current study revealed that milled resins had similar surface roughness as rapidly-prototyped resins, therefore the null hypothesis regarding the surface roughness of milled and rapidly-prototyped CD resins is not rejected. However, this study did reveal that resins printed with the recommended 3D-printer had significantly smoother surfaces than the resins printed with a third-party 3D-printer. Hence, the null hypothesis regarding the influence of use of the 3D-printer on the surface roughness of rapidly-prototyped CD resins is rejected...

It is important to bear in mind that in this study, only a few CAD-CAM denture resin materials have been investigated. Therefore, results cannot be generalized to all milled and 3D-printed resins currently available in the market.

5. Conclusions

Within the limits of this present study, the following conclusions are drawn:

1. CAD-CAM milled and rapidly-prototyped complete denture resins are similar in their biocompatibility and surface roughness.
2. CAD-CAM milled denture resins exhibit better mechanical properties than rapidly-prototyped resins.
3. The printing orientation as well as the use of third-party 3D-printers can affect the resin strength and their surface roughness.

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CRediT authorship contribution statement

Murali Srinivasan: Conceptualization, Methodology, Validation, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. Nicole Kalberer: Methodology, Validation, Resources, Writing – review & editing, Project administration. Porawit Kannoedboon: Validation, Formal analysis, Resources, Writing – original draft, Writing – review & editing, Visualization. Mustapha Mekki: Methodology, Investigation, Validation, Resources, Investigation, Data curation, Writing – review & editing. Stephane Durual: Methodology, Investigation, Validation, Resources, Investigation, Data curation, Writing – review & editing. Mutlu Ozcan: Methodology, Validation, Resources, Writing – review & editing, Supervision. Frauke Müller: Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no conflict of interests.

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Appendices

Appendix 1. Study design diagram illustrating various tests with sample sizes and sample dimensions for each resin group. MB, Milled Base; MT, Milled Tooth-shade; PB1, Printed Base with recommended 3D-printer; PB2, Printed Base with third-party 3D printer; PB2V, Printed Base with vertical orientation; PT, Printed Tooth-shade.

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