

Laboratory Evaluation of Novel Implant Metal-Acrylic Prosthesis Design: Influence of Monolithic Acrylic Veneer

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Purpose: To test a novel implant metal-acrylic prosthesis design in comparison to a conventional prosthesis design through simulation of cyclic masticatory loading. The novel design involved digital designing and fabrication of the framework and the matched veneering acrylic resin material. **Materials and Methods:** Ten prostheses were fabricated for each group. All the prostheses exhibited a similar external design on two implants with a distal cantilever. The conventional group comprised a milled metal framework with mechanically retained acrylic denture teeth via vertical pins. The digital prosthesis group incorporated an inverted T-shape bar and a monolithic milled acrylic resin veneer. The resin veneer was subsequently adhesively attached on the bar. All prostheses were thermally aged and subjected to laboratory cyclic loading at the cantilever region. The load-to-failure and the number of cycles until failure were collected. Furthermore, failed specimens were analyzed to determine the mode of failure. **Results:** The digital prostheses failed at significantly greater load-to-failure ($1,570.0 \text{ N} \pm 116.0 \text{ N}$) and number of cycles ($124,857 \pm 21,608$) than the conventional prostheses (load-to-failure = $1,015.0 \text{ N} \pm 47.4 \text{ N}$; number of cycles = $28,452 \pm 6,559$). The conventional prostheses failed by fracturing of the acrylic teeth and veneering material that led to exposure of the metal framework. Half of the digital prostheses failed by superficial chipping of the veneering material, while the other half failed by the deformation and fracture of screws. **Conclusion:** Within the limitations of this study, the digital prostheses with the novel design and monolithic veneering material showed significantly higher strength compared with the conventional prostheses. The mode of acrylic failure of the digital prostheses was more favorable. *INT J ORAL MAXILLOFAC IMPLANTS* 2020;35:100–106. doi: 10.11607/jomi.7545

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The discovery of osseointegration and the outstanding outcomes of implant treatment led to this treatment approach being widely embraced for the management of partial and complete edentulism.¹ One of the solutions for long-span edentulous spaces

is the implant fixed hybrid prosthesis, in which a metal framework supports artificial teeth and acrylic resin.^{2–4} Although this concept entails multiple advantages such as relative ease of fabrication, and ability to efficiently restore missing teeth and tissues, it still has several reported disadvantages. For example, most of the existing clinical studies on metal-acrylic prostheses have reported that chipping of the veneering material is the primary prosthetic complication.^{5–11} The rate of acrylic veneer complications was reported to be in the range of 20% to 30%.^{12–14} While fracturing of the acrylic veneer may seem to be an easily managed mechanical complication, it directly affects the function, esthetics, and comfort of the patient. Further, little attention has been paid to the clinical time and resources required for this supplementary treatment, or its impact upon both the clinician and the patient.^{15,16} In addition, cases of very frequent acrylic veneer chipping may mandate complete replacement of the prosthesis. Therefore, there is a need to develop new material and design concepts to reduce the incidence and severity of acrylic veneer chipping.

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More recently, implant frameworks have been produced by computer-aided design/computer-assisted manufacturing (CAD/CAM), where the framework is digitally designed and fabricated from milling a solid blank of commercially pure titanium, titanium alloy, or base-metal alloy via a computer numeric controlled (CNC) machine. Such a manufacturing approach was proven to be efficient in producing accurate, customizable, and durable frameworks.^{17–20} This method of fabrication has been tested against cast framework and has shown similar clinical outcomes.^{21–23} However, all these advantages are related to the performance of metal frameworks and have minimal influence on the veneering material. This project tested a concept that extends the application of CAD/CAM to produce the veneering acrylic resin in addition to the metal framework. Specifically, it evaluates a novel implant metal-acrylic prosthesis design where the whole prosthesis is designed digitally, including the metal framework and the veneering acrylic resin. The metal framework is designed with an inverted T-shape and produced by milling, while the monolithic veneering acrylic resin shell is designed to complete the shape of the prosthesis and fit against the metal framework. After producing the monolithic veneering acrylic resin via milling, it is attached to the metal framework by adhesive cementation. In comparison to the conventional implant prosthesis, the digital prosthesis has the advantages of simplicity, less manual handling, and less reliance on dental technicians. The use of monolithic veneering material is envisioned to reduce the likelihood of veneering material mechanical complications. Therefore, the aim of this project was to evaluate the mechanical performance of the veneering material on digital prostheses in comparison to conventional prostheses after thermal cycling and simulated chewing movement. Two variables were evaluated in the study: (1) load-to-failure and (2) number of cycles. The null hypothesis was that both groups will have similar load-to-failure and number of cycles until failure.

MATERIALS AND METHODS

Prosthesis Fabrication

Two implant-prosthesis groups were evaluated in the study: conventional and digital prostheses. All the prostheses had similar external design and dimensions. A virtual prosthesis was digitally planned to extend from the maxillary second incisor to the first molar (35 mm total length), and was designed to fit on two external-hex Brånemark implants (4.0 mm diameter) at the location of the maxillary canine and second premolar. The implants were 15 mm apart, and a short distal 10-mm cantilever was included in the design at

the region of the first molar. The cantilever was used subsequently for loading. All metal frameworks were manufactured from grade 5 commercially pure titanium by 5-axis CNC machine (DMG MORI). The two types of prostheses were designed and produced by the same commercial milling center (Osteon Medical).

The titanium framework of the digital prosthesis group consisted of an inverted T-shape cross section. The design allowed monolithic CAD/CAM material (composite-infused poly[methyl methacrylate] [PMMA]) to be mechanically and adhesively retained (Fig 1a). The line angles of the internal surfaces of the framework were designed to be rounded. The veneering material shells were milled in one piece from a single block to fit over the vertical component of the metal framework. The veneering material had a flexural strength of 120 MPa, flexural modulus of $3,200 \pm 300$ MPa, and Vickers hardness 180 ± 5 . The acrylic material was milled with a 50- μ m offset at the vertical internal surfaces to serve as cement space. The horizontal ledge area was designed with no offset to ensure accurate seating of the acrylic veneer.

The titanium framework of the conventional group was designed to mechanically retain conventional acrylic denture teeth via five retentive vertical pins. Each pin corresponded to an acrylic tooth, and its dimensions were 5 mm in height and 2 mm in diameter (Fig 1b). In an attempt to achieve standardization, the acrylic teeth used for the conventional group were milled using the same composite-infused PMMA material as the one used for the digital prostheses. In addition, the milling process provided for controlled teeth dimensions and incorporated holes to fit over the retentive pins of the conventional framework. This ensured that teeth for all 10 specimens of the conventional group were of the same size and dimensions, as well as eliminating the need for adjustments ordinarily conducted for denture teeth to fit over frameworks. The holes were milled with 1-mm radial offset incorporated in the design to allow for acrylic flow between the teeth and the vertical pins.

All metal frameworks of both groups were treated by sandblasting using Al_2O_3 (110 μ m) at a pressure of 2.5 to 3.5 bars. For the digital prosthesis group, in order to adhesively bond the two prosthesis components, the metal frameworks were primed using MKZ Primer (Bredent), and the veneering material was primed using Visio-link PMMA Composite Primer (Bredent). The veneering material was subsequently cemented to the frameworks under normal finger pressure using Panavia SA Cement Plus (Kuraray Dental) following the manufacturer's instructions. For the conventional group, a commercial processing protocol was followed by an experienced master dental technician. To ensure maximum consistency, a silicone putty index

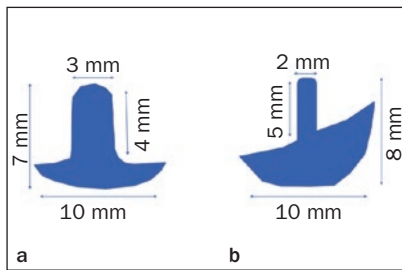


Fig 1 Schematic drawing of a cross section in the titanium frameworks of (a) digital group and (b) conventional group.

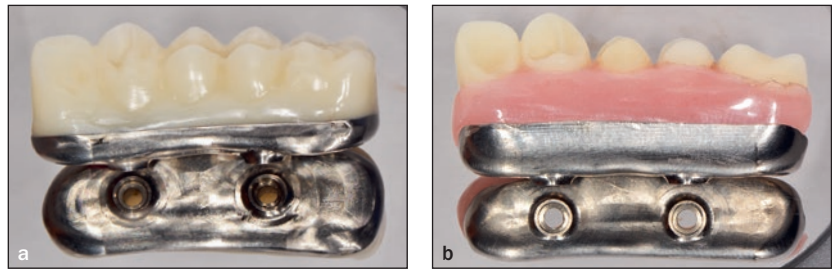


Fig 2 Completed specimen of (a) digital group and (b) conventional group.

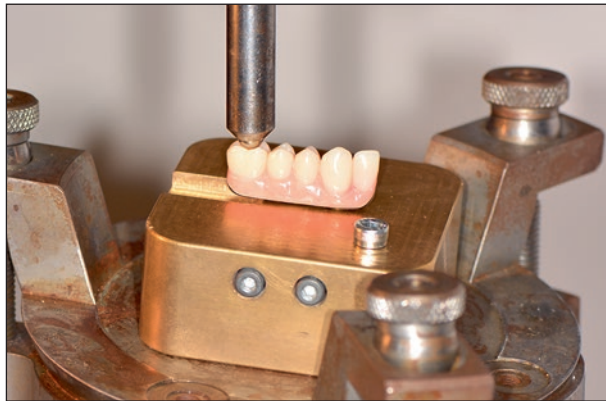


Fig 3 Clamping block with a secured specimen loaded on the cantilevered unit.

was fabricated using one digital prosthesis. The index was used to control the position of the acrylic teeth on the conventional framework of the 10 specimens. The specimens were then invested, flaked, and processed using heat-cured PMMA (Vertex Rapid Simplified, Vertex Dental) according to the manufacturer's instructions. All samples were finished and polished in the same manner. Figure 2 shows completed specimens of digital and conventional prostheses.

Loading

To simulate the clinical scenario, all the prostheses were artificially aged by subjecting them to laboratory thermal cycling via immersion in two water baths of 5°C and 55°C for 5,000 cycles (JWE).²⁴ Each cycle was 60 seconds and divided equally between the baths. This protocol replicated 6 months of intraoral service. Subsequently, every prosthesis was cyclically loaded in a chewing simulator until failure. This was executed by mounting the prosthesis on a customized brass block. For each prosthesis, a new set of implant analogs were used and attached to the brass block by lateral screws. The brass block was then secured to the platform of the cyclic loading machine (MTS 810 Materials Test System, MTS Systems). All frameworks were

screw-retained to the implant analogs by the proprietary screws torqued as per the manufacturer's recommendations to 35 Ncm using a manual torque wrench (Nobel Biocare). Perpendicular loads were applied at the mesial fossa of the maxillary first molar (Fig 3). A ball applicator of 4 mm diameter was used to apply load as it touched the cuspal inclines of the molar in three points, creating three vectors of magnitude in different directions. During loading, moisture levels were maintained by covering the specimens with saline-saturated gauze. Stepped fatigue cyclic loading commenced with an initial load of 750 N, followed by incrementally increasing load to 1,000 N, 1,150 N, 1,300 N, 1,400 N, 1,500 N, 1,600 N, and finally, 1,700 N. Each load value was maintained for 20,000 cycles. The advantage of this testing protocol is that it offered a better recreation of clinical conditions than static load testing without involving an extended period of testing time. The cyclic loading continued until a prosthesis failure was confirmed by audible or visible crack, sudden increase in displacement of the specimen away from the loading plate, or a sudden reduction in the force applied to the specimen. For each prosthesis, the load-to-failure increment and the number of cycles until failure were recorded. In addition, the patterns of failure were also determined for every prosthesis.

Statistical Analyses

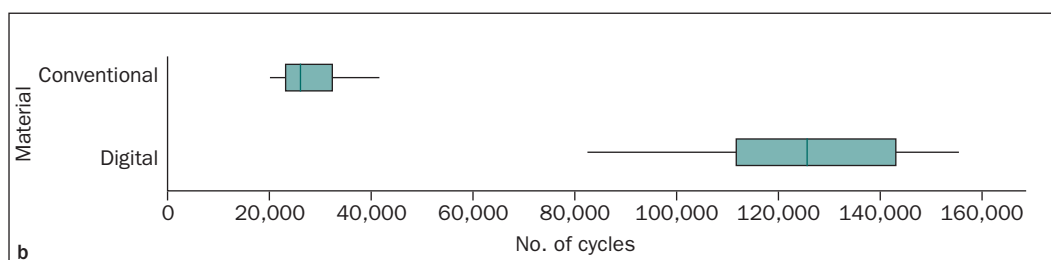
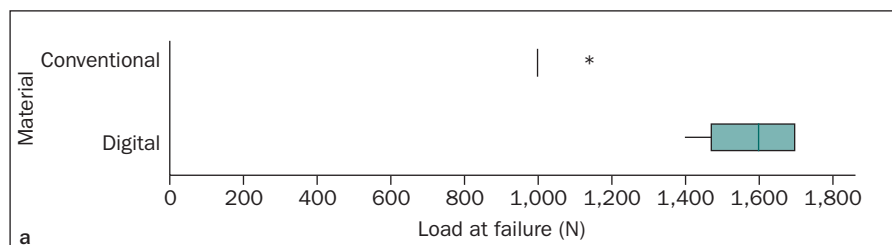
The means and standard deviations of the load-to-failure and the number of cycles were calculated for each group. The Mann-Whitney *U* test was used to evaluate the difference between the digital and conventional prostheses. The statistical analyses were carried out using statistical software (Minitab Statistical Software, v18, Minitab). The level of significance was .05 for all the statistical analyses.

RESULTS

All the results are summarized in Table 1. The digital prosthesis group failed at a significantly greater load

Table 1 Mean, Standard Deviation, Median, and Minimum and Maximum of Number of Cycles and Loads at Failure for Both Groups

	Material	Mean	SD	Median	Minimum and maximum
No. of cycles	Conventional	28,452	6,559	26,823	20,512–42,356
	Digital	124,857	21,608	125,929	82,741–156,965
Load at failure	Conventional	1,015	47.4	1,000	1,000–1,150
	Digital	1,570	116.0	1,600	1,454–1,686

Fig 4 (a) Load at failure and (b) number of cycles until failure, conventional vs digital.

(1,570.0 N \pm 116.0 N) than the conventional group (1,015.0 N \pm 47.4 N) ($P < .001$). Nine conventional prostheses failed precisely at the same load increment (1,000 N), and one conventional prosthesis failed at the 1,150 N increment (Fig 4a). The digital prostheses failed at approximately 50% higher loads, where the lowest load at failure increment was 1,400 N. The digital prosthesis group fractured after a significantly higher number of cycles (124,857 \pm 21,608) than the conventional group (28,452 \pm 6,559) ($P < .001$). In order to fracture, the digital prostheses required more than 4 times the number of cycles of the conventional prostheses (Fig 4b).

All the conventional prostheses failed due to acrylic teeth and veneer fracture, where the crack propagated through the acrylic tooth and the veneering resin. The crack traveled through the bulk of the material until it reached the metal framework, causing significant bulk chipping of the acrylic and exposing the metal framework (Fig 5a). Five digital prostheses failed by fracture of the milled acrylic veneer. The acrylic fracture initiated on the occlusal surface at the area of load application and propagated through the veneering material until separation of the acrylic (Fig 5b). All acrylic failures were cohesive fractures, and the chipped fragments were restricted to the superficial 1 to 2 mm of

the material. No metal frameworks were exposed as a result of the chipping. The other five digital prostheses did not show failure of the acrylic material. Instead, the screw distant from the loading site failed at loads between 1,600 and 1,700 N. The screws failed by deformation of the screwhead (Fig 5c).

DISCUSSION

The study indicated a significant difference in the outcome of the digital prosthesis design compared with the conventional design, where the novel design showed a promising outcome within the parameters of this study. Therefore, the null hypothesis that both designs will have similar load-to-failure and number of cycles until failure was rejected. The observed superiority of the digital prostheses over the conventional prostheses can be attributed to the veneering material and the design of the metal framework.

Failure of acrylic veneering material in the conventional prostheses can be related to the existence of multiple interfaces between the individual acrylic teeth, between the teeth and the pink acrylic resin, and, furthermore, between the acrylic base and the metal framework. Literature reporting on acrylic resin

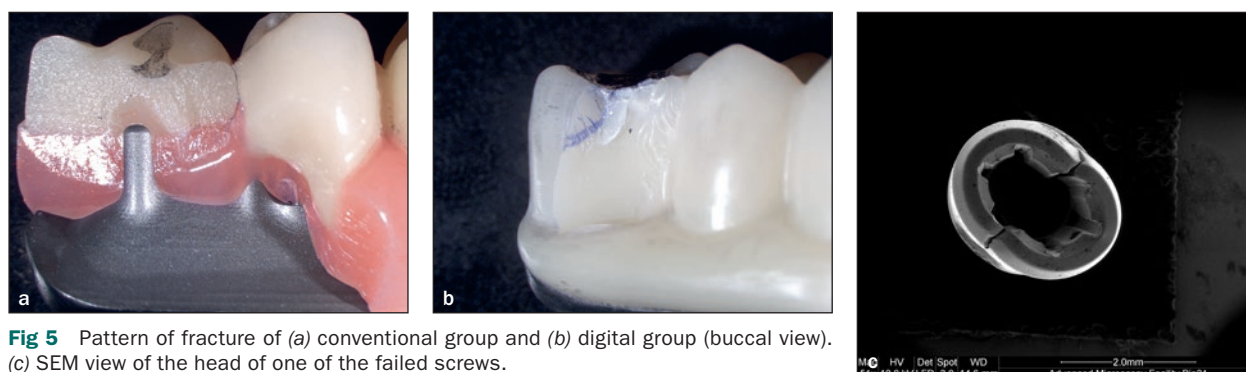


Fig 5 Pattern of fracture of (a) conventional group and (b) digital group (buccal view). (c) SEM view of the head of one of the failed screws.

failures discussed the stress concentrations occurring at the interface of acrylic teeth and acrylic bases,²⁵ showing that separation of the acrylic tooth from the veneering material eventually occurs during function. This has been clearly observed through the pattern of failure of conventional prostheses. In addition, the failure rate of the acrylic resin material is further increased by human factors introduced during the veneering process.²⁶ This produces processing errors, such as entrapped air and moisture,²⁷ contamination of the bonding surfaces of teeth with impurities during laboratory processing,²⁸ deformation of acrylic,²⁹ and inconsistency of processing and polishing. All these accumulated deficiencies can contribute to crack initiation and propagation during function. Moreover, the presence of vertical pins within the processed prostheses leads to inevitably thin occlusal acrylic and introduces areas of stress concentrations at the tips of the pins. The literature reported stress concentrations occurring around the embedded metal frameworks.³⁰ The effect of stress concentration around the pin is confirmed in the present study, as the fracture pattern of all the conventional prostheses is related to pin location where acrylic bulk fractures exposed the pin and the underlying metal framework. This is further accentuated by the vertical orientation of the pins in line with the occlusal forces that creates excessive stresses at the pin tip.³¹

On the other hand, the digital prosthesis design and fabrication avoided most of the conventional prosthesis limitations. For example, the failure patterns of digital prostheses were different from the failure patterns of conventional prostheses. Specifically, the failure of acrylic veneer on digital prostheses was more favorable and less catastrophic. As the milled veneer material is machined by CNC processing from a single industrial block, it possesses greater homogeneity and minimal imperfections such as internal flaws and porosities.^{32,33} As a result, the monolithic acrylic veneer is more resistant to crack propagation in any particular direction. This was evident from the present study by the superficial veneer

chipping (1 to 2 mm of the external veneer surface) and lack of exposure of underlying metal framework. As the veneering material is digitally designed, the manufacturer can also ensure it has acceptable minimal thickness to withstand functional loading. Likewise, digitally designing the metal framework ensured sufficient bulk of framework to resist deformation at the cantilever region. Contrary to the conventional prosthesis frameworks, the horizontal bar design with rounded occlusal surface of the metal framework of the digital prostheses seemed to further reduce stress concentration regions. This is proven by the present study by the observation that none of the metal frameworks were exposed after acrylic veneer failure.

Despite the expectations that the cement interface would constitute the weakest point of the digital prosthesis setup, there were no observed failures within the cement layer. Lack of failures within the cement line could be attributed to the small cement space provided in the design of the prosthesis and the implemented adhesive cementation protocol. As the horizontal ledge area was designed with no offset, a minimal gap was created at all junctions exposed to the oral environment. This design reduces the rate of cement dissolution that can occur if exposed to a wet environment over an extended period of time.³⁴

According to this study, the digital prosthesis design appears to be promising in reducing the occurrence and severity of acrylic veneer chipping, where even the lowest load-to-failure for the digital prosthesis material remained considerably higher than the load-to-failure for the conventional group. This is clearly outlined by the fact that half of the tested digital prostheses did not suffer from acrylic failure. Instead, these prostheses failed by screw deformation and fracture at the implant analog distant from the loading site. This is due to the considerable tensile forces manifested at the distant implant, eventually leading to the screw failure. However, this is not anticipated in a clinical scenario as the magnitude of physiologic occlusal forces would not ordinarily reach the levels

attained in this experiment.³⁵ On the other hand, the acrylic veneer chipping that had occurred on the other five prostheses was superficial in comparison to the more significant failures of conventional prostheses. Clinically, it may be speculated that failure of digital prostheses can easily be managed by polishing and simpler repair, which is convenient to the patient and the clinician. This is an important observation, as the predominant complication pattern of fixed implant prostheses is chipping and fracture of veneering material.⁵ Further, even if severe chipping is encountered clinically, new veneering material can be milled and cemented to the existing metal framework. Nevertheless, the digital prosthesis design requires more validation prior to routine clinical application. In the present laboratory study, monochromatic and monolithic material was used for the veneer. This may not provide the most desirable esthetic outcome. To improve the esthetics, pre-shaded monolithic blocks with gradient color should be applied clinically. Further, to improve appearance, the replaced gingival tissues should be tinted with pink color. It is anticipated that this extra interface would have its own complications within a clinical scenario. As a result, the impact of these modifications on the prosthesis durability should be validated in additional studies. Moreover, the practicality and clinical outcome of digital prostheses need validation by clinical studies. As the conventional and digital prostheses failed at loads much higher than the physiologic limits (approximately 800 N on posterior teeth),³⁵ it can be speculated that the two prosthesis designs are clinically acceptable. Thus, despite the different results in terms of number of cycles until failure and loads at failure, both groups remain satisfactory, as loads sustained by the two groups were higher than loads ordinarily reached intraorally. Therefore, the clinical significance of the difference between the groups is yet to be determined.

While the setup of the experiment aimed to simulate the clinical scenario as closely as possible by thermal cycling and chewing simulation, it will never account for the complexity of natural function. For example, constant incremental increases in the loading for both groups do not reflect the true physiologic nature of mastication. Further, the lateral masticatory movements were not simulated in this study.

CONCLUSIONS

Within the limitations of this study, the digital prostheses with the novel veneering concept showed considerably higher strength in laboratory setup under cyclic loading than conventional prostheses. This was reported in terms of the number of cycles sustained until

failure, as well as the magnitude of load-to-failure. Furthermore, the mode or pattern of fracture of the digital prostheses appeared more favorable compared with the conventional group.

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