Penetration depth of monomer systems into acrylic resin denture teeth used as pontics

Leila Perea, DDS, MSc,a Jukka P. Matinlinna, MSc, PhD,b Mimmi Tolvanen, PhD,c Francesco Mannocci, MD, DDS, PhD,d Timothy F. Watson, BDS, PhD, FDS,e and Pekka K. Vallittu, DDS, PhDf

Acrylic polymer-based denture teeth are used in the prosthetic rehabilitation of removable and fixed dental prostheses (FDPs). They could be used as pontics in inlay-retained E-glass fiber-reinforced composite (FRC) FDPs if the adhesion of the teeth to the prosthesis is adequate. This could represent an alternative therapy option to conventional complete coverage FDPs, resin-bonded FRCs, or implant-supported treatments.1,2 Restorations made of FRC3-5 may enable the development of cost-effective treatment approaches with tooth structure conservation6 and improved esthetic outcomes. The application of FRC FDPs for the replacement of missing teeth may be simplified with the use of acrylic resin denture teeth as pontics, which may also increase the types of applications under which FRC FDPs can be used.7,8 Complications related to the delamination of the veneering composite resin from the FRC framework, chipping fractures,9-11 wear,9 and discoloration11 have been observed.

ABSTRACT

Statement of problem. The ways of softening and dissolving the surface of acrylic resin denture teeth need to be specified to obtain more durable prosthetic treatments that include resin denture teeth.

Purpose. The purpose of this study was to analyze the penetration depth of 4 monomer systems applied during different exposure times on the acrylic resin denture teeth used as pontics of directly fabricated fiber-reinforced composite fixed dental prostheses. The penetration depth contributes to the adhesion of the tooth to the adhesive resin.

Material and methods. Ninety-six specimens were divided into 3 groups according to the acrylic resin denture tooth used: Artic 8 (Heraeus Kultzer), experimental tooth (GC), and Vitapan (Vita). Each group was divided into 4 subgroups according to the monomer system used: methylmethacrylate (99%), composite primer, a flowable composite resin, and a photopolymerizing dimethacrylate resin. The 4 monomer systems were labeled with rhodamine B to determine their penetration depth into the acrylic resin denture teeth. After exposure times of 1, 5, 15, and 60 minutes, the monomers were photopolymerized for 5 minutes, with the exception of methylmethacrylate. The specimens were cut orthogonally from gingival to occlusal in 4 slices (n=8/subgroup). The penetration depths of monomers were measured by a confocal scanning type microscope. Differences in the penetration depths were evaluated with ANOVA.

Results. ANOVA (R²=.699) revealed significant differences in the penetration depths according to the exposure times (P<.001), monomers (P<.001), brands used (P=.047), and their mutual interaction (P<.001).

Conclusions. The ability of monomers to penetrate the surface of acrylic resin denture teeth was influenced by the monomer systems, which might improve the bond between the pontics and the fiber-reinforced composite frameworks of fixed dental prostheses. (J Prosthet Dent 2015;113:480-487)
**Clinical Implications**
A deeper penetration of monomer systems into acrylic resin denture teeth used as pontics in fiber-reinforced composite fixed dental prostheses may improve the clinical effectiveness of these prostheses.

Different types of acrylic resin denture teeth have been introduced to increase their abrasion resistance, improve their adhesive properties, and enhance their esthetics. Acrylic resin denture teeth are frequently made from polymethyl methacrylate (PMMA) beads and color pigments in a cross-linked polymer matrix. In order to maintain their excellent toughness and convenient handling while improving their wear resistance, new types of acrylic resin denture teeth have been developed with a higher degree of cross-linking between the polymers and the use of special prepolymer.

Another approach to the improvement of the mechanical properties and wear resistance has been the addition of organic and inorganic filler particles, such as silicon dioxide (silica), to the polymer matrix of acrylic resin denture teeth and modifications to their interfaces. The inorganic fillers are treated with a silane-coupling agent (silanization) to enhance adhesion to the organic matrix base of the acrylic resin denture teeth. Artificial teeth made from a polymeric matrix consisting of urethane dimethacrylate reinforced with inorganic filler particles are also available. Polymer technologies such as blend polymers, interpenetrated polymer networks (IPN), and double cross-linking are used to develop cross-linked acrylic resin denture teeth. Cross-linking agents are widely used to improve strength and crazing resistance. A cross-linked acrylic resin denture tooth contains a so-called semi-IPN, defined as the outer layer of the polymer beads into which the monomers of the matrix have diffused during the processing of the tooth.

The cross-linked polymer matrix of an acrylic resin denture tooth is unevenly distributed: the incisal or occlusal area of the tooth may be highly cross-linked, and the gingival ridge-lap surface may be less cross-linked. The less cross-linked structure in the ridge-lap surface facilitates better chemical bonding of the acrylic resin denture tooth to the FRC structure by the secondary IPN formation. This increased bonding might be achieved by the linear polymer cores of the PMMA beads of denture teeth, which have not formed a semi-IPN structure because they have not been affected by the monomers of the matrix. During the formation of the secondary IPN, the polymer is dissolved by the solvent molecules of the monomer, which allows the monomer to penetrate the solvent-rich surfaces.

The effectiveness of a monomeric solvent in dissolving and penetrating the PMMA depends on the exposure time, type of monomeric solvent, temperature, and the polymeric structure of the substrate. A previous study reported the effect of different monomers systems on the surface hardness of acrylic resin denture teeth achieved by increasing the monomer’s exposure time: the longer the exposure time of the monomers, the lower the surface hardness of the denture teeth surfaces before polymerization of the monomers. That might mean that by increasing the exposure time of the monomers on the acrylic resin denture tooth surfaces, a deeper penetration may be achieved. To the authors’ knowledge, no published reports exist on the penetration depth of dimethacrylate monomer systems into acrylic resin denture teeth. Nevertheless, this information could prove important in terms of improving the adhesive properties of those denture teeth used as pontics in fiber-reinforced composite fixed dental prostheses (FRC FDPs).

The purpose of this study was to analyze the penetration depth of 4 monomer systems applied during different exposure times on acrylic resin denture teeth. The null hypothesis was that no variation would be seen in the dissolving ability of the monomer systems used on the acrylic resin denture tooth surfaces. In addition, a prolonged exposure time of the monomer systems on the surface of acrylic resin denture teeth would not be relevant in terms of increasing monomer penetration depths.

**MATERIAL AND METHODS**

The materials used in the current study are listed in Table 1. Three brands of acrylic resin denture tooth were selected: Artic 8 (Heraeus Kultzer), experimental tooth (GC), and Vitapan (Vita). Mandibular acrylic resin denture molars were chosen to be evaluated. An autopolymerizing acrylic resin (Palapress; Heraeus Kultzer) was used as a base material into which the acrylic resin denture teeth were bonded. A total of 96 specimens were prepared. The ridge-lap surfaces of the denture teeth were then wet ground (MetaServ 3000 Grinder-Polisher; Buehler), with up to 1200-grit (FEPA) silicon carbide abrasive paper under running water as a coolant. Each specimen was ultrasonically cleansed (Nusonics GP70; Quayle Dental) in deionized water for 10 minutes and allowed to dry under ambient laboratory conditions (23°C ±1°C) for 60 minutes.

Four monomer systems were used: methylmethacrylate 99% (MMA; Sigma-Aldrich), composite primer (GC), a flowable composite resin (Stick Flow; StickTech-GC), and a photopolymerizing dimethacrylate resin (Stick Resin; StickTech-GC). The specimens were divided into 3 study groups according to the brand used. Each group was divided into 4 subgroups according to the monomer system used. Finally, each subgroup was...
subdivided and subjected to the following 4 exposure times: 1, 5, 15, and 60 minutes.

The monomer systems of each subgroup were mixed with a fluorescent dye (Rhodamine B; Sigma-Aldrich Corp) and then applied to the specimen’s ridge-lap surfaces with a fine microbrush. The specimens were then stored under a light-protection shield (Viva Pad; Ivoclar Vivadent) for the corresponding exposure time to allow the monomers to penetrate the acrylic resin denture teeth. At the end of the predetermined exposure time, the monomer systems were photopolymerized for 5 minutes with a handheld light-polymerizing unit (Optilux 500; Demetron-Kerr) with a 450 mW/cm² irradiation output. No polymerization was undertaken in the subgroup where MMA was used as a monomer system. The MMA was left in contact with the acrylic resin denture tooth surfaces, which were covered by a shield to avoid monomer evaporation.

Each specimen was sectioned orthogonally from gingival to occlusal in 4 slices with a microtome saw (IsoMet 1000 Precision Saw; Buehler). A total of 8 slices were included in each experimental subgroup. The slice thickness was 1 mm. A schematic drawing of the process is shown in Figure 1. The sectioned surfaces of the slices were polished with up to 2400 grit (FEPA) silicon carbide abrasive paper under running water as a coolant. Each slice was ultrasonically cleaned in deionized water for 10 minutes and allowed to dry under ambient laboratory conditions (23°C ±1°C) for 60 minutes.

Specimen slices were fixed on glass microscope slides. The measurement of the penetration depth of monomers into the acrylic resin denture teeth was made with a confocal scanning type microscope (TSM; Noran Instruments). Specimens were examined by using the ×60 and ×100 oil immersion objectives. For each slice, the deepest penetration depth (µm) of the monomer system along the acrylic resin denture tooth surface was measured by using the ×100 oil immersion objective. The patterns of the penetration depths were evaluated by 1 examiner (L.P.) with analyzing software (iQ; Andor Technology). An image of the deepest penetration was recorded from each slice with an electron multiplying charge-coupled device (iXon 885 EM-CCD; Andor Technology). The data were then registered and transferred onto a spreadsheet for subsequent statistical analysis.

The means and standard deviations (SD) were calculated for the penetration depths according to

---

**Table 1. Materials used**

<table>
<thead>
<tr>
<th>Name</th>
<th>Manufacturer</th>
<th>Batch No.</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artic 8</td>
<td>Heraeus Kultzer</td>
<td>12112200981</td>
<td>PMMA, dimethacrylate</td>
</tr>
<tr>
<td>Vitapan Cusiform</td>
<td>Vita M6</td>
<td></td>
<td>PMMA, dimethacrylate</td>
</tr>
<tr>
<td>GC (experimental tooth)</td>
<td>GC</td>
<td></td>
<td>PMMA, dimethacrylate</td>
</tr>
<tr>
<td>Palapress</td>
<td>Heraeus Kultzer</td>
<td>012531</td>
<td>Powder: PMMA-copolymer Liquid: MMA, dimethacrylate, butanediol dimethacrylate, alcoxylated polyol tetraacrylate, additives</td>
</tr>
<tr>
<td>Methylmethacrylate, 99%</td>
<td>Sigma-Aldrich</td>
<td>576535-139</td>
<td>MMA</td>
</tr>
<tr>
<td>Stick FLOW</td>
<td>StickTech-GC</td>
<td>5104628</td>
<td>bis-GMA, TEGDMA, camphorquinone and amine activator</td>
</tr>
<tr>
<td>Composite Primer</td>
<td>GC</td>
<td>1208012</td>
<td>Monofunctional methacrylate, UDMA, camphorquinone and amine activator</td>
</tr>
<tr>
<td>Stick Resin</td>
<td>StickTech-GC</td>
<td>5107797</td>
<td>bis-GMA, TEGDMA, camphorquinone and amine activator</td>
</tr>
<tr>
<td>Rhodamine B</td>
<td>Sigma-Aldrich</td>
<td>47H3506</td>
<td>Dye content 97%</td>
</tr>
</tbody>
</table>

PMMA, polymethylmethacrylate; MMA, methylmethacrylate; bis-GMA, bis-phenol A-glycidyl dimethacrylate; TEGDMA, triethyleneglycol dimethacrylate; UDMA, urethane dimethacrylate; NA, not available.

---

**Table 2. Penetration depths in µm (SD) of monomer systems into acrylic resin denture teeth according to exposure time**

<table>
<thead>
<tr>
<th>Brand</th>
<th>Monomer System</th>
<th>1 min (µm)</th>
<th>5 min (µm)</th>
<th>15 min (µm)</th>
<th>60 min (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artic 8 Composite Primer</td>
<td>1.01 (0.28)</td>
<td>2.74 (0.52)</td>
<td>2.78 (0.26)</td>
<td>2.78 (0.33)</td>
<td></td>
</tr>
<tr>
<td>MMA</td>
<td>0.24 (0.08)</td>
<td>0.28 (0.10)</td>
<td>0.25 (0.08)</td>
<td>0.68 (0.25)</td>
<td></td>
</tr>
<tr>
<td>Flowable composite</td>
<td>2.10 (0.62)</td>
<td>2.29 (0.35)</td>
<td>2.66 (0.37)</td>
<td>4.47 (0.71)</td>
<td></td>
</tr>
<tr>
<td>Stick Resin</td>
<td>1.80 (0.23)</td>
<td>2.21 (0.28)</td>
<td>2.30 (0.57)</td>
<td>2.26 (0.28)</td>
<td></td>
</tr>
<tr>
<td>GC Composite Primer</td>
<td>1.17 (0.36)</td>
<td>1.20 (0.35)</td>
<td>1.28 (0.31)</td>
<td>1.98 (0.41)</td>
<td></td>
</tr>
<tr>
<td>MMA</td>
<td>0.56 (0.23)</td>
<td>0.94 (0.38)</td>
<td>1.15 (0.40)</td>
<td>2.15 (1.33)</td>
<td></td>
</tr>
<tr>
<td>Flowable composite</td>
<td>2.46 (0.30)</td>
<td>3.77 (0.53)</td>
<td>3.70 (0.88)</td>
<td>3.72 (0.49)</td>
<td></td>
</tr>
<tr>
<td>Stick Resin</td>
<td>1.93 (0.42)</td>
<td>2.53 (0.34)</td>
<td>2.63 (0.28)</td>
<td>2.65 (0.29)</td>
<td></td>
</tr>
<tr>
<td>Vitapan Composite Primer</td>
<td>1.69 (0.30)</td>
<td>1.64 (0.42)</td>
<td>1.71 (0.40)</td>
<td>2.09 (0.24)</td>
<td></td>
</tr>
<tr>
<td>MMA</td>
<td>0.67 (0.20)</td>
<td>0.94 (0.48)</td>
<td>0.89 (0.40)</td>
<td>3.95 (1.12)</td>
<td></td>
</tr>
<tr>
<td>Flowable composite</td>
<td>2.82 (0.48)</td>
<td>3.26 (0.63)</td>
<td>3.32 (0.73)</td>
<td>5.08 (1.21)</td>
<td></td>
</tr>
<tr>
<td>Stick Resin</td>
<td>0.21 (0.14)</td>
<td>1.58 (0.23)</td>
<td>1.98 (0.36)</td>
<td>1.90 (0.29)</td>
<td></td>
</tr>
</tbody>
</table>

---

**Figure 1. Schematic drawing of test specimen. Before sectioning (A), sectioning in 1 mm slices (B), and vertical slice (C).**
Figure 2. Morphological patterns of monomer diffusion into acrylic resin denture tooth surfaces. Upper part (bright side) of all photos correspond to monomer system and lower part (dark side) to denture tooth; intermediate zone (interface) shows penetration depth. A, Original flat tooth surface. B, Reflection mode confocal image of acrylic resin denture tooth-monomer interface. C, Fluorescence mode image of area shown in B. D, Different pattern observed in reflection mode. E, Fluorescence mode of area shown in D.
exposure times and to the acrylic resin denture teeth brand, monomer system, and their interaction. Univariate analysis of variance (ANOVA) was then used to evaluate mean differences between the variables. The differences between the exposure times were also evaluated by using curve estimation—a separate model for each brand and monomer system. The linear and quadratic models were estimated and compared according to their $R^2$ values and statistical significances. All analyses were conducted with software (SPSS v19.0 for Windows; IBM Corp).

RESULTS

The differences observed in the penetration depths of the monomer systems into the tested acrylic resin denture teeth are listed in Table 2. ANOVA ($R^2=.699$) revealed differences according to the acrylic resin denture tooth brand ($P=.047$), monomer system ($P<.001$), exposure time ($P<.001$), and their mutual interaction ($P<.001$). The highest penetration depth value (5.08 µm) was found in the Vitapan group when a flowable composite resin was used as a monomer system for 60 minutes. Throughout the evaluation, a continuous dissolution layer of different thickness was found as a morphological pattern of interdiffusion in the test groups (Fig. 2). Differences in the structural composition of the tested acrylic resin

---

**Figure 3.** Structural composition of acrylic resin denture teeth studied. A, Artic 8. B, GC. C, Vitapan (original magnification, ×500).

**Figure 4.** Penetration depths (µm) of monomer systems used in Artic 8 group.
denture teeth were observed by scanning electron microscopic (SEM) examination. Vitapan teeth suggested a multiphasic structure of cross-linked matrix, which was not observed in the Artic 8 and GC teeth (Fig. 3).

The quadratic curve estimations showed slightly higher $R^2$ values than did the linear curve estimations. The results of the models in the Artic 8 group are represented in Figure 4. Figure 5 shows the results found in the GC group and Figure 6 in the Vitapan group. These figures show the interaction of the penetration depths achieved with the 4 monomer systems used according to the selected exposure times. A significant association was found between the penetration depth and the acrylic resin denture tooth brands, monomer systems, and exposure times.

**DISCUSSION**

The results of the present study support the rejection of the null hypothesis. The monomer systems used had the ability to dissolve the acrylic resin denture tooth surfaces. A prolonged exposure time of the monomer systems on the surface of acrylic resin denture teeth increased the monomers’ penetration depths. This experimental study was designed to investigate the penetration depths of different monomers into acrylic resin denture tooth surfaces. The focus was on analyzing the possibilities of dissolving the ridge-lap surfaces of the denture teeth to improve the success of using acrylic resin denture teeth as pontics for FRC FDPs. The penetration depths were visualized by using a confocal scanning type microscope and subsequently measured. Three brands of acrylic resin denture tooth, Artic 8, Vitapan, and GC, were used in order to consider the potential differences in the outcomes according to their polymeric structures. The chemical composition of the tested acrylic resin denture teeth was roughly similar. Although they consisted of PMMA and dimethacrylates, SEM examination revealed some differences in their respective structural compositions; Artic 8 and GC showed a similar composition, while in Vitapan a multiphasic structure of cross-linked matrix was observed.

The interdiffusion of monomers into a polymeric structure could be obtained if the polymer substrate contains a linear polymer such as PMMA and if the monomers have a dissolving capability against the linear polymer phases of the substrate.20,23 This requires that the solubility of the linear polymer in organic solvents is close to that of the monomer system used.28 Given this, the solubility parameter is a measure of the ability of the liquid to dissolve and soften solid (plastic) surfaces. When the diffused monomers are bifunctional, such as bisphenol A-glycidyl dimethacrylate (bis-GMA) or triethylenglycol dimethacrylate (TEGDMA), which are commonly used components in the monomer systems, the multiphase polymer structure formed after polymerization is a semi-interpenetrating polymer network (semi-IPN). The semi-IPN is best described as a result of the combination of a cross-linked polymer system such as bis-GMA-TEGDMA and the linear PMMA.23 In this study, 4 monomer systems were used to dissolve the denture tooth surfaces, which were then assumed to show differences in terms of their effectiveness in swelling and dissolving the superficial PMMA.
The exposure time is one of the key aspects in the dissolution gradient of solvents to dissolve and penetrate a polymeric structure. In the current study, the selected exposure times of 1, 5, 15, and 60 minutes were included. Methylmethacrylate (MMA) applied for 3 minutes to the surface of acrylic resin denture teeth has been suggested to produce a strong bond in denture tooth repairs by the formation of a secondary IPN layer. MMA was one of the monomers tested in this study. It produced the lowest penetration depth value in the 3 denture tooth brands and during the first 3 exposure times (1, 5, and 15 minutes), with the exception of Vitapan teeth when MMA was used for 60 minutes, resulting in a depth of 3.95 μm. However, between the monomers tested, it is not accurate to conclude that MMA would be less effective in dissolving the polymeric structure of acrylic resin denture teeth. The MMA volatility represented a challenge to maintain it on the tooth surface during long treatment times. The mentioned MMA volatility and the fact that it did not remain as a sufficiently thick layer on the denture tooth surface, as was the case with the other monomers studied, could have contributed to the difficulty of observing and measuring its penetration depth into the acrylic resin denture tooth surfaces.

Confocal scanning microscopy was used in this study as a visualization technique in preference to other microscopic methods such as SEM. As reported previously in studies focused on FRC-based polymers, fluorescence imaging using rhodamine B allowed the monomer diffusion to be traced into the surfaces. However, a disadvantage of the confocal scanning microscopy is that the scattered fluorescent light might simulate broader infiltration zones than are actually present under reflected light imaging. Considering that, in this study, all specimens were analyzed under the fluorescence and reflection mode as a visualization technique.

A previous study measured the surface hardness of the teeth before polymerization of the monomers and reported that the surfaces of acrylic resin denture teeth became softer when the monomer exposure time was increased. The changes in the denture tooth surfaces probably occurred because of a deeper penetration of the monomers. In the current study, a greater penetration depth was observed in proportion to the increase in the exposure time.

From the monomer systems tested, the flowable composite resin used (Stick Flow) showed the highest penetration depth (5.08 μm). At higher temperatures, the bond strength of denture base polymer to denture teeth is increased as a result of the deeper penetration of the monomers of the denture base polymers into the denture teeth. That said, in this study, the monomer systems used were not heat polymerized. However, the photopolymerization time used was 5 minutes, and heat could have been generated during the polymerization. That heat might also have allowed the activators, initiators, and monomers of the flowable composite resin to diffuse into the acrylic resin denture tooth surfaces. In addition, the fillers of the resins may have limited the penetration of light, resulting in apparently less penetration depths of the monomers.

Because an image analysis can only give a description of the micromorphological material characteristics, further studies should focus on testing the performance of acrylic resin denture teeth used as pontics in FRC FDPs with the above-described pretreatment conditions.

**CONCLUSIONS**

The ability of some monomers to penetrate the surface of acrylic resin denture teeth is influenced by the selection of the monomer systems. An appropriate choice may improve the bond between the pontics and the FRC frameworks of FDPs.

---

**REFERENCES**


Corresponding author:
Dr Leila Perea
Turku Clinical Biomaterials Centre-TCBC
University of Turku
Itäinen Pitkäkatu 4B (2nd floor)
FI-20520 Turku
FINLAND
Email: leila.perea@utu.fi

Acknowledgments
The authors thank Stick Tech Ltd (member of GC group) for generously providing materials for the study, and Peter Pilecki for his valuable technical assistance.