Fracture Resistance of Two Different Composite Resin CAD/CAM Crowns Bonded to Titanium Abutments

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Purpose: To determine the influence of thermal and mechanical cycling on fracture load and fracture pattern of resin nanoceramic crowns and polymer-infiltrated ceramic-network (PICN) crowns, both fabricated with CAD/CAM technology. Materials and Methods: A total of 90 premolar crowns bonded to titanium abutments were divided into three groups of 30 crowns each: 30 resin nanoceramic crowns (LU); 30 PICN crowns (VE); and 30 metal-ceramic crowns (MC). The 30 specimens of each group were further divided into three subgroups of 10 each that underwent (1) no treatment, (2) thermocycling (2,000 cycles, 5°C to 55°C), and (3) thermocycling with subsequent mechanical cycling (120,000 cycles, 80 N, 2 Hz). The specimens were loaded to failure, and two-way ANOVA and chi-square test were used to determine differences in fracture resistance and pattern. Results: Mechanical and thermal cycling significantly influenced the critical load to failure of the three materials; however, no significant differences were observed between the thermocycled materials and the materials that were thermocycled with subsequent mechanical cycling. The MC specimens experienced significantly higher fracture loads than those of the LU and VE specimens, which showed no differences from each other in fracture resistance. The fracture pattern depended on the material and was unrelated to the type of treatment it underwent. Conclusion: All crowns showed adequate resistance to normal masticatory forces in the premolar area. The cyclic fatigue load negatively influenced all three materials. Int J Prosthodont 2020;33:648–655. doi: 10.11607/ijp.6421
esthetics and resistance.5,19 Among the advantages of CAD/CAM technology are its automated production process, precise and consistent fabrication, electronic storage of production steps, superior reproducibility,20–22 and cost-effective manufacturing. To meet esthetic demands and provide superior physical properties for permanent dental restorations, CAD/CAM technology is also used, with new and improved machinable materials for chairside-fabricated indirect restorations.4,5,8,20,23,24

After the introduction of the first chairside CAD/CAM system in 1985,25 delivery of ceramic restorations in a single appointment became a treatment option. In recent years, not only has the system become more affordable, easier, faster, and more accurate, but it is also being used to fabricate indirect composite resin restorations. To ensure consistent quality, these composite resins are industrially polymerized under standardized parameters at a high temperature and a high pressure.26 This process has led to more sophisticated and enhanced mechanical properties, allowing for the fabrication of indirect composite resins for single complete-crown units, inlays, onlays, and veneers.5,23,27,28 CAD/CAM restorations are usually fabricated from the two aforementioned categories of restorative blocks developed for chairside systems. The fact that these blocks are shaped or milled with a wet grinding process in less than 20 minutes allows for delivery of the definitive restoration in a single appointment.25 Thus, chairside CAD/CAM restorations cut chair time and eliminate the need for temporary restorations.29 The system may also be used to fabricate aesthetic ceramic or composite resin crowns for an implant abutment during a single visit.25,30–33

Patients usually demand uncompromising esthetic results for the restoration of anterior teeth. The esthetic importance of premolars for the smile means that they are considered as anterior teeth, but they receive greater occlusal forces than the other anterior teeth due to their position. In other words, crowns fabricated from new materials containing a polymeric matrix require sufficient strength and fracture resistance to high occlusal loading in the premolar area. However, to the authors’ knowledge, no quantitative analysis has been conducted on the longevity of these crowns seated on premolars.4,34

The first CAD/CAM system used in both the dental office and the laboratory, the CEREC 3 CAD/CAM (Dentsply Sirona), was introduced more than 20 years ago.23 The latest materials used for the CEREC system include resin nanoceramic (Lava Ultimate [LU] Restorative, 3M ESPE)9 and polymer-infiltrated ceramic network (PICN) (VITA ENAMIC [VE], VITA Zahnfabrik). According to the manufacturers, these two materials bring together some of the best properties of ceramics and composite resins,35–37 although there are limited studies on the survival and success rates of these two CAD/CAM–fabricated restorations.5,38 Despite the breakthroughs in esthetics, biocompatibility, and the mechanical properties of ceramic restorations and composite resin materials, the effects of mechanical and thermal loading in the oral cavity may still be cause for concern.39 Fatigue and fracture of these materials may be influenced by rapid changes in thermal, physical, and chemical conditions.31,40–43 Hence, investigation into mechanical and thermal cycling is needed to ascertain the mechanical properties of ceramic and composite resin materials. Since in vivo studies are costly and time consuming, laboratory investigation of clinical performance is more common.41

The aim of this study was to determine the influence of thermal and mechanical cycling on fracture load and fracture pattern of two types of CAD/CAM–fabricated crowns: resin nanoceramic crowns (LU) and PICN (VE) crowns. Metal-ceramic (MC) crowns served as a control group. The null hypotheses were that, regardless of the material used to fabricate the crowns and the treatment they underwent, no statistically significant differences would be found in either failure load or fracture pattern.

**MATERIALS AND METHODS**

This study evaluated the fracture resistance and pattern of two types of composite resin CAD/CAM crowns using conventional MC crowns as a control group. Ninety (90) titanium abutments (5 mm in diameter, 6 mm in height, with a 6-degree taper angle and a 0.5-mm–deep chamfer finish line) were industrially fabricated from a monoblock (titanium body and abutment) according to a design simulating an implant body and a prosthetic abutment. The titanium bodies were embedded in acrylic resin to simulate an osseointegrated implant.31,44 The abutments were designed with a smooth flat face, which served as a position indicator to stabilize the crown (Fig 1). Ninety identically shaped crowns for a maxillary right second premolar were fabricated from three materials and then bonded on titanium abutments and divided into three groups: 30 LU, 30 VE, and 30 MC. The LU

**Fig 1** Titanium abutment used in the study.
and VE groups were CAD/CAM fabricated, and the MC group was manufactured using a conventional technique. Table 1 shows the characteristics of the materials tested. The CAD/CAM crowns were fabricated using a CEREC AC unit with Dentsply Sirona software (version 4.0.2). Digital impressions of the abutment and the surrounding structure were taken with CEREC Bluecam (Dentsply Sirona).11 Each abutment was masked with VITA Powder Scan Spray (VITA Zahnfabrik) to create the opaque surface needed for scanning with an optical 3D intraoral camera to obtain a virtual cast. After delineating the chamfer finish line, each crown was designed using the biocopy project, which reproduces the anatomy of the tooth before preparation. In the present study, the anatomy of the premolar was obtained before the tooth was removed from the maxillary typodont resin model (Frasaco USA).31,45,46 After verifying that all the crown surfaces measured at least 2 mm in thickness, the crown was saved. The LU and VE groups were milled with Cerec inLab MC XL (Dentsply Sirona), and the MC group was fabricated with a conventional technique by duplicating the shape of the CAD/CAM crown. To reproduce the crown anatomy, the technician took an impression of the crown, which served as a guide for waxing each crown.

### Specimen Treatment Processes

All abutments were airborne-particle abraded with alumina oxide (50 µm) above the restoration outline.47,48 LU and VE crowns were bonded with an adhesive resin (RelyX Ultimate, 3M ESPE), and the intaglio surfaces of each crown were treated in accordance with each manufacturer’s instructions:

- **LU intaglio surfaces** were abraded with 50-µm aluminum oxide particles, which were removed with ethanol and air dried with compressed air for 30 seconds.49,50
- **VE intaglio surfaces** were etched with 5% hydrofluoric acid gel (IPS Ceramic Etching Gel, Ivoclar Vivadent) for 60 seconds, cleaned with a water spray, cleaned ultrasonically in distilled water for 60 seconds, and lastly air dried with compressed air for 30 seconds.3

A ceramic primer containing a silane-coupling agent (Monobond Plus, Ivoclar Vivadent) was applied to the LU and VE intaglio crown surfaces and allowed to dry for 60 seconds. The LU and VE crowns were pretreated with a bonding agent (Scotchbond Universal, 3M ESPE). The MC crowns were cemented with a self-adhesive resin (RelyX Unicem, 3M ESPE).51 Before cementation, intaglio surfaces were abraded with 50-µm aluminum oxide particles, which were removed with ethanol and air dried with compressed air for 30 seconds. After seating each crown, excess cement was removed from the margin. Then, the buccal, occlusal, and lingual surfaces were light polymerized (Radii Plus, SDI) for 20 seconds. One hour after cementation, all specimens were stored at 100% humidity and 37°C for 24 hours. The 30 specimens of each group were divided into three subgroups (n = 10):

- **Subgroup 1**: No treatment
- **Subgroup 2**: 2,000 thermal cycles between two water baths of 5°C and 55°C with a dwell time of 30 seconds at each temperature.
- **Subgroup 3**: Same thermocycling procedure as for subgroup 2, with subsequent mechanical cyclic loading with a chewing simulator (Chewing Simulator CS-4, SD Mechatronik), producing a total of 120,000 masticatory cycles at a load of 80 N with a vertical movement of 2 mm at 2 Hz.53–57

After the different treatments, all specimens were loaded to failure. Fracture resistance was tested with a servohydraulic testing machine (Bionix 370, MTS Systems).

### Table 1 Characteristics of Materials Tested

<table>
<thead>
<tr>
<th>Type</th>
<th>Brand (manufacturer)</th>
<th>Composition matrix filler</th>
<th>Lot no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite resin nanoceramic</td>
<td>Lava Ultimate (3M ESPE)</td>
<td>20 nm silica filler, 4–11 nm zirconia filler, 0.6–10 um silica-zirconia clusters, UDMA</td>
<td>N515666</td>
</tr>
<tr>
<td>Polymer infiltrated ceramic network</td>
<td>VITA ENAMIC (VITA Zahnfabrik)</td>
<td>Silicon dioxide (60%), aluminum oxide, sodium oxide, UDMA, TEGDMA</td>
<td>35040</td>
</tr>
<tr>
<td>Metal</td>
<td>Metal: Heraeus P Bonding Alloy (Heraeus-Kulzer)</td>
<td>Cr (25%), Co (59%), Mo (4%), W (10%), Mn (0.8%), Si (1%), N (0.2%)</td>
<td>12747</td>
</tr>
<tr>
<td>Ceramic</td>
<td>Ceramic: VITA VM 13 (VITA Zahnfabrik)</td>
<td>Feldspathic ceramic</td>
<td>48330</td>
</tr>
</tbody>
</table>

Cr = chromium; Co = cobalt; Mn = manganese; Mo = molybdenum; N = nitrogen; W = tungsten; Si = silicon; TEGDMA = tri-ethylene-glycol-dimethacrylate; UDMA = urethane dimethacrylate.
with a load cell of 25 kN at a crosshead speed of 1 mm per minute, according to ISO standard 6872:2008.\textsuperscript{58} An 8-mm stainless steel ball was used to apply a load on two cusps.\textsuperscript{4,59} The compression load, recorded in Newtons, was applied parallel to the long axis of the crown until failure. Subsequently, the failure types were visually evaluated by a single experienced operator (S.F.) and classified into three fracture pattern groups: (1) chipping (cohesive failure of the ceramic veneer only); (2) partial fracture (part of the crown still bonded to the abutment); and (3) complete fracture (crown was completely fractured and debonded from the abutment) (Fig 2).

The sample size for the fracture resistance assessment was determined from the results of a pilot test with three samples of each material. A variance of 8,962.06 N was calculated. A 95% confidence level, 90% power, 150-N precision, and bilateral hypothesis were established. The resulting sample size adjusted for losses of 5% was 9 samples per group; therefore, 10 was chosen as the sample size. This value is in line with similar studies.\textsuperscript{21,31,42}

Data were statistically analyzed using Statgraphics Centurion XV version 15.1.02 (Statpoint Technologies). The values of the specimens were first verified to ensure they followed a normal distribution (Shapiro-Wilk test, \( P > .05 \)) and that homogeneity of variance was acceptable for performing parametric tests. Subsequently, two-way (treatment and material) analysis of variance (ANOVA) was performed to determine whether there were significant differences in fracture resistance among the three materials. Chi-square test was used to determine possible differences in the fracture pattern of the materials. A confidence level of 95\% was used in all tests.

**RESULTS**

None of the crowns fractured during treatment. Table 2 summarizes the fracture resistance data obtained after all the tested materials underwent the different treatments. It also shows the fracture resistance of the variation (treatment or material) vs the control (untreated). The relative SD (RSD) results revealed small values, which could indicate high reliability. The group with the lowest reliability was the MC crowns that underwent thermal and mechanical cycling (28.25\%), while the group with the highest reliability was the LU crowns that underwent thermal cycling only (14.30\%). The results of the two-way ANOVA (Table 3) showed that mechanical and thermal cycling significantly affected the critical load to failure of the three materials (\( P < .05 \)). However, no significant difference was observed among groups for undergoing thermal cycling alone compared to undergoing thermal cycling with subsequent mechanical cycling. Regardless of the type of treatment used, the MC crowns showed significantly higher fracture loads than those of the LU and VE crowns (\( P < .05 \)). No significant differences were observed in fracture load between LU and VE.

Interaction between the independent variables of the treatment and the material showed significant differences (\( P < .05 \)). In spite of the different treatments used, MC produced better results in fracture load, but it was the only group affected by the treatment it received, suggesting a considerable reduction in resistance. The fracture patterns of the materials differ according to the material, but not according to the type of treatment the material underwent. Table 4 shows the incidence of the three different fracture patterns (chipping, partial fracture, complete fracture). Regardless of the material, both types of metal-free crowns were shown to fracture mesiodistally, but the vestibular part remained bonded to the abutment in about 50\% of them. Chi-square test performed with a \( P < .05 \) value showed a relation between material and fracture pattern, but no relation between treatment and fracture pattern (\( P > .05 \)).
Table 2  Fracture Resistance (N) of All Groups

<table>
<thead>
<tr>
<th>Material</th>
<th>Treatment</th>
<th>Mean</th>
<th>SD</th>
<th>RSD (%)</th>
<th>Fracture resistance variation vs treatment control (%), mean ± SD</th>
<th>Fracture resistance variation vs material control (%), mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No treatment</td>
<td>1,142.43a</td>
<td>279.50</td>
<td>24.47</td>
<td>Control</td>
<td>43.20 ± 13.90</td>
</tr>
<tr>
<td>Lava Ultimate</td>
<td>Thermal cycling</td>
<td>1,183.30a</td>
<td>169.16</td>
<td>14.30</td>
<td>3.59 ± 14.81</td>
<td>20.80 ± 11.32</td>
</tr>
<tr>
<td></td>
<td>Thermal cycling and mechanical cycling</td>
<td>1,043.50a</td>
<td>199.26</td>
<td>19.10</td>
<td>8.65 ± 17.44</td>
<td>29.51 ± 13.46</td>
</tr>
<tr>
<td></td>
<td>No treatment</td>
<td>1,136.30a</td>
<td>228.46</td>
<td>20.11</td>
<td>Control</td>
<td>43.51 ± 11.36</td>
</tr>
<tr>
<td>VITA ENAMIC</td>
<td>Thermal cycling</td>
<td>977.00a</td>
<td>161.26</td>
<td>16.51</td>
<td>14.01 ± 14.19</td>
<td>34.61 ± 10.79</td>
</tr>
<tr>
<td></td>
<td>Thermal cycling and mechanical cycling</td>
<td>936.70a</td>
<td>183.65</td>
<td>19.61</td>
<td>17.56 ± 16.16</td>
<td>36.73 ± 12.41</td>
</tr>
<tr>
<td></td>
<td>No treatment</td>
<td>2,011.20b</td>
<td>352.50</td>
<td>17.53</td>
<td>Control</td>
<td>Control</td>
</tr>
<tr>
<td>Metal-ceramic</td>
<td>Thermal cycling</td>
<td>1,494.00b</td>
<td>326.91</td>
<td>21.88</td>
<td>25.72 ± 16.25</td>
<td>Control</td>
</tr>
<tr>
<td></td>
<td>Thermal cycling and mechanical cycling</td>
<td>1,480.40b</td>
<td>418.28</td>
<td>28.25</td>
<td>26.39 ± 20.80</td>
<td>Control</td>
</tr>
</tbody>
</table>

SD = standard deviation; RSD = relative standard deviation. Different superscript letters denote significant differences between groups.

Table 3  Results of Two-Way ANOVA

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Sum of squares</th>
<th>Degrees of freedom</th>
<th>Mean square</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>1.25407E+06</td>
<td>2</td>
<td>6.27033E+05</td>
<td>8.49</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Material</td>
<td>7.17988E+06</td>
<td>2</td>
<td>3.58994E+06</td>
<td>48.62</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Treatment*material</td>
<td>9.03217E+06</td>
<td>4</td>
<td>2.25804E+05</td>
<td>3.06</td>
<td>.021</td>
</tr>
<tr>
<td>Error</td>
<td>5.98097E+06</td>
<td>81</td>
<td>7.38392E+04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1.53181E+07</td>
<td>89</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4  Fracture Patterns

<table>
<thead>
<tr>
<th>Material</th>
<th>Chipping</th>
<th>Partial fracture</th>
<th>Complete fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lava Ultimate</td>
<td>0</td>
<td>56.6</td>
<td>43.4</td>
</tr>
<tr>
<td>VITA Enamic</td>
<td>0</td>
<td>53.34</td>
<td>46.66</td>
</tr>
<tr>
<td>Metal-ceramic</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

All data are reported as %.
DISCUSSION

This investigation assessed the influence of thermal and mechanical cycling on fracture load and fracture patterns of groups LU and VE, with MC as a control group. The interaction between the material and the thermal/mechanical treatment indicates that fracture resistance for MC was significantly greater than for LU and VE crowns, which showed no statistical difference from each other. Fracture resistance values for thermal and mechanical cycling treatment vs no treatment were significantly lower for the treated MC crowns and were similar for the treated LU and VE crowns. According to these results, the null hypothesis of the nonstatistically significant differences in fracture load for the materials used to fabricate the crowns was rejected. Likewise, the null hypothesis of no statistically significant differences in fracture load for treatment for the MC crowns was rejected, although it was accepted for the LU and VE crowns. Regarding fracture pattern, significant differences were observed for the materials, but not for the treatment they received; thus, the null hypothesis for materials was rejected, and the null hypothesis for treatment they underwent accepted.

A similar methodology used in a previous study showed that fracture resistance and treatment method yielded similar results to those of the metal-free restorations used in the present study, in which, irrespective of the treatment, no statistically significant differences were shown. In contrast, other studies found that thermocycling and cyclic loading treatments adversely affected the strength of both composite resin and ceramic CAD/CAM crowns. Unlike simultaneous thermocycling and cyclic loading for artificial aging of crowns, which affect resistance, the method of thermocycling alone or thermocycling followed by cyclic loading—both of which were used in the present study—showed no statistically significant differences. Two types of treatment were not performed simultaneously, which might explain the different results obtained from the two previously mentioned studies. It is also important to note that the crowns tested in those studies were cemented on teeth, not on implant abutments. 15,21

Of the three crowns under study, MC was the most resistant to fracture. While LU and VE values were less resistant, they were similar to those obtained in previous studies, who cemented metal-free crowns on implant abutments to analyze fracture resistance of different materials, found no differences between LU and VE, findings that concur with those of the present study study. In contrast to the present study, Carvalho et al observed high values of fracture resistance for metal-free crowns, which could be explained by their use of tooth abutments.

Mechanical and thermal cycling in vitro methodologies are used to simulate conditions of restorations in the oral cavity. A 5-year service usually requires 1,200,000 mechanical cycles, although 6,000 thermal cycles can also be used to measure the same span. Simulation time in the present study was reduced to approximately 2 years by selecting 120,000 dynamic loading cycles and 2,000 thermal cycles, in accordance with previous studies. Resistance values recorded by Lauvahutanon et al suggest that the type of material and treatment conditions were significantly affected by the treatment received. Those authors also evaluated the same metal-free materials (LU and VE) used in the present study following a similar methodology (7-day water storage and 10,000 thermocycles), but with different times (24-hour storage and 120,000 thermocycles). In contrast, their study found differences in the two materials after thermocycling, affecting the flexural strength and modulus of CAD/CAM composite resin blocks such as LU, and only slightly for VE. These two materials were not affected by the thermal process, and no differences were observed between them in the present study. These findings might be explained by the different storage times and thermocycling procedures.

In addition to the fracture load values, the type of failure was also analyzed, as this affects the prognosis of the crown. Metal-free crown fractures are regarded as catastrophic because they are nonreparable, as reported by other authors. Regardless of the material, the LU and VE crowns were shown to fracture in the buccal and palatal parts, leaving the abutment intact, in concordance with Stona et al. In nearly half of the metal-free crowns studied, one part of the crown remained bonded to the abutment in the vestibular part, which is consistent with the results of other authors. This may be explained by the crown design, which has a vestibular and palatal cusps, and the way in which the force of the steel ball was applied on the two cusps. Although the LU and VE crowns fractured in the same way, the abutments to which the VE crowns were bonded showed no cement on the abutment surface (as observed in a previous study), but the abutments on which the LU crowns were bonded did show cement on their surface. This may be a consequence of bonding and adhesion problems of the LU crowns.

The results of both the present study and those of a previous one suggest that the LU and VE crowns bonded to solid abutments were sufficiently resistant to normal masticatory forces applied on premolars, which suggests a clinically acceptable level of fracture resistance, considering that the maximum occlusal forces range from 222 to 445 N in the premolar region. While the present study was ongoing, 3M ESPE announced that the complete-coverage crown was no longer indicated...
for LU due to a higher-than-anticipated debonding issue, although this product continues to be indicated for inlays, onlays, and veneer restorations.34

The results of the laboratory tests should be considered carefully, since in vitro studies cannot reproduce the conditions in the oral cavity. The fracture resistance in the present study is relative rather than absolute, and the extrapolation of these in vitro resistance data to the clinical situation should be viewed with caution and considered within the limitations of this study. The present study showed that LU and VE offer a promising technique to fabricate monolithic crowns bonded directly to solid abutments, thereby restoring function and esthetics in a single visit. However, in determining the most adequate material to use, the clinician must consider the patient’s age, parafunctional habits, and masticatory forces, as well as the cost of materials and labor.

CONCLUSIONS

Within the limitations of this study, the tested CAD/CAM crowns—resin nanoceramic crowns (Lava Ultimate) and PICN (VITA ENAMIC)—cemented to machined titanium abutments might be considered adequate for short-term use in the premolar area. It is important to consider that these two crowns are less resistant than conventional MC crowns.

Regarding crown fracture patterns, LU and VE both showed nonreparable fracture, whereas the ceramic part of MC might be reparable, as these crowns fractured by chipping.

ACKNOWLEDGMENTS

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Literature Abstract

A Prospective Study on the Effect of Coronal Tooth Structure Loss on the 4-year Clinical Survival of Root Canal Retreated Teeth and Retrospective Validation of the Dental Practicality Index

The aims of this study were, first, to examine the impact of residual volume of coronal tooth structure as measured with an intraoral scanner on the 4-year clinical survival of root canal–retreated teeth, and, second, to retrospectively assess the effectiveness of the Dental Practicality Index (DPI) in predicting the survival of root canal–retreated teeth. A total of 156 posterior root canal–treated teeth (140 patients) had baseline periapical radiographs and CBCT scans taken prior to root canal retreatment. These teeth were followed up with clinical examinations at 1, 2, 3, and 4 years (T12, T24, T36, and T48), with periapical radiographs and CBCT images taken at T12, and periradicular radiographs taken at T24, T36, and T48 when appropriate. Root canal–retreated teeth were dichotomized into survived vs extracted. Fisher exact test was used to determine the association between the volume of remaining coronal tooth structure and 4-year tooth survival. The DPI for each tooth was established using the preoperative clinical and radiographic data. Fisher exact test was used to establish a relationship between categorical variables (total DPI score and tooth outcome). The percentage of extractions associated with teeth with <29.5% remaining coronal tooth structure was 3 times higher (12.5%) compared to that of teeth with a residual tooth structure >29.5% (3.5%), but with no significant difference (P = 0.073). There was a significant correlation between the outcome of root canal retreatment at 1 year, assessed by both PA and CBCT, and 4-year survival (P = 0.007 and P = 0.001, respectively). Teeth with a DPI score ≥ 6 were more likely to be extracted than teeth with a DPI score < 6 (18.8% vs 3.9%) (P = 0.045). Teeth with <30% of remaining tooth structure were associated with a survival rate above 80%, and teeth with >30% residual tooth structure survived in more than 94% of cases. The radiographic outcome of root canal treatment can also help to predict tooth survival, with teeth having an unfavorable outcome at 1 year more likely to be extracted within 4 years of completion of treatment. The DPI score can potentially be used to identify teeth with failed root canal treatment, which are likely to be extracted following retreatment and cuspal coverage.