Effect of a Two-step Placement Procedure on the
Dislocation Resistance of a Methacrylate Resin-based
Root Canal Sealer: A Proof of Concept

Amir T. Moinzadeh\textsuperscript{a} / Hesam Mirmohammadi\textsuperscript{b} / Tjibbe Veenema\textsuperscript{c} / Cornelis J. Kleverlaan\textsuperscript{d} / Paul R. Wesselinke\textsuperscript{e} / Min-Kai Wu\textsuperscript{f} / Hagay Shemesh\textsuperscript{g}

**Purpose:** To investigate whether the placement of a methacrylate root canal sealer or a conventional epoxy root canal sealer in two steps increases their dislocation resistance when compared to a one-step placement procedure.

**Materials and Methods:** Eighty single-rooted teeth were randomly allocated to 4 groups (n = 20). All canals were instrumented to size 40, 0.06 taper and irrigated according to a standardized protocol. Root canal filling was conducted as follows: group 1: methacrylate sealer placed in two steps; group 2: methacrylate sealer placed in one step; group 3: epoxy sealer placed in two steps; group 4: epoxy sealer placed in one step. After setting, thin slices at different root levels were obtained and submitted to push-out testing. Results were analyzed with non-parametric tests to compare the two-step procedures to their one-step counterparts. Failure modes were determined by stereomicroscopy. Random untested methacrylate sealer specimens were also examined with scanning electron microscopy.

**Results:** At each root level, dislocation resistance was significantly higher for the two-step procedure than for the one-step procedure using the methacrylate sealer (p = 0.003, p = 0.005, p < 0.001) but not the epoxy sealer (p = 0.83, p = 0.1, p = 0.06). Among root levels, there were no significant differences in dislocation resistance in the methacrylate sealer two-step group, while all other groups showed differences.

**Conclusion:** A two-step placement procedure resulted in significantly higher dislocation resistance for the methacrylate sealer but not for the epoxy sealer.

**Keywords:** adhesion, configuration factor, dislocation resistance, methacrylate resin, polymerization shrinkage, root canal sealer.

\textsuperscript{a} PhD Student, Department of Endodontology, Academic Center for Dentistry Amsterdam, University of Amsterdam and VU University, Amsterdam, The Netherlands. Hypotheses, experimental design, push-out testing, statistical analysis, manuscript redaction.

\textsuperscript{b} Guest Researcher, Department of Endodontology, Academic Center for Dentistry Amsterdam, University of Amsterdam and VU University, Amsterdam, The Netherlands; Assistant Professor, Dental Materials Research Center, Department of Restorative Dentistry, School of Dentistry, Isfahan University of Medical Sciences, Isfahan, Iran. Idea development, experimental design, failure mode evaluation, contribution to discussion.

\textsuperscript{c} Postgraduate Resident, Department of Endodontology, Academic Center for Dentistry Amsterdam, University of Amsterdam and VU University, Amsterdam, The Netherlands. Specimen preparation, failure mode evaluation, proofreading, contribution to discussion.

\textsuperscript{d} Associate Professor, Department of Material Science, Academic Center for Dentistry Amsterdam, University of Amsterdam and VU University, Amsterdam, The Netherlands. Material sciences input, manuscript reviewing.

\textsuperscript{e} Professor Emeritus, Department of Endodontology, Academic Center for Dentistry Amsterdam, University of Amsterdam and VU University, Amsterdam, The Netherlands. Idea development, supervision, contribution to discussion.

\textsuperscript{f} Guest Senior Researcher, Department of, Endodontology, Academic Center for Dentistry Amsterdam, University of Amsterdam and VU University, Amsterdam, The Netherlands. Idea development, contribution to discussion.

\textsuperscript{g} Assistant Professor, Department of Endodontology, Academic Center for Dentistry Amsterdam, University of Amsterdam and VU University, Amsterdam, The Netherlands. Endodontic aspects input, manuscript editing.

Correspondence: Amir T. Moinzadeh, Department of Endodontology, office 2N25, Gustav Mahlerlaan 3004, 1081 LA, Amsterdam, The Netherlands. Tel: +31 20 598 453. e-mail: a.moinzadeh@acta.nl

\textsuperscript{6} Methacrylate resin-based sealers (MRBS) have been introduced in endodontics in an effort to improve the adhesion and sealing ability of the root canal filling. However, the polymerization shrinkage occurring within the material because of the high configuration factor (C-factor) encountered in root canals may be a severe limitation to their application.\textsuperscript{15} The C-factor is the ratio of the bonded surfaces to the unbonded ones.\textsuperscript{8} The root canal
could be regarded as a class I cavity with an extremely high C-factor because of its elongated geometry.\textsuperscript{25} Such a constrained cavity is expected to hamper the flow of the sealer, and the shrinkage resulting from the polymerization may result in shrinkage stress, compromising the bonding and possibly leading to the detachment from dentin or from the obturation cone.\textsuperscript{2,13} If this occurred, the root canal seal would be compromised.\textsuperscript{21}

One strategy to minimize the polymerization shrinkage could be to reduce the C-factor by placing MRBS with an incremental technique. In the root canal, the two-step placement of restorative polymer resins has shown to significantly increase dislocation resistance compared to a single-step technique.\textsuperscript{3,13} However, none of the previous studies investigating two-step placement procedures within the root canal used controls with materials relatively insensitive to the C-factor. Furthermore, root canal sealers present different properties than restorative materials, and it would therefore be interesting to verify whether incrementally placed MRBS behave in a manner similar to restorative resins. Currently used root canal sealers present extended setting times, which precludes clinical applicability of this technique without the use of accelerators. Furthermore, an improvement in the dislocation resistance by a two-step placement procedure could motivate manufacturers to implement relevant modifications in sealer properties.

RealSeal SE (Kerr; Orange, CA, USA) mainly comprises ethoxylated bisphenol-A-dimethacrylate (EBPA-DMA), 2-hydroxyethyl methacrylate bisphenol-A-glycidyl dimethacrylate (bis-GMA), and acidic monomers. The degree of conversion of a resin relates to its monomeric conversion of carbon-carbon double bonds into polymeric carbon-carbon single bonds.\textsuperscript{27} By decreasing resin viscosity and increasing monomer mobility, the bis-GMA and acidic methacrylate monomers of the RealSeal SE increase its degree of conversion, which in turn results in better biocompatibility and bonding but also in higher polymerization shrinkage.\textsuperscript{22} The degree of conversion of RealSeal SE is between 74.53\% ± 7.02 and 77.20\% ± 5.36 and the shrinkage stress its non-self-etching version (RealSeal) undergoes is 4.47\% ± 0.15.\textsuperscript{12,27}

AH Plus is a bisphenol epoxy-resin–based root canal sealer (BRBS) and is mainly composed of bisphenol-A-diglycidyl ether, adamantane amine, and diamines. It is considered a gold standard to which other sealers may be compared.\textsuperscript{7,19,20} Its degree of conversion lies between 74.4\% ± 16.6 to 82.7\% ± 1.9 and its dimensional change upon setting is -0.034\% ± 0.01.\textsuperscript{1,29} Its molecular structure and polymerization mechanism\textsuperscript{16} make it less susceptible to polymerization shrinkage compared to MRBS, and it thus served as a suitable control for the purpose of the present study.

The aim of the present study was to investigate whether the placement of a MRBS or a conventional BRBS in two steps increases their dislocation resistance when compared to a one-step placement procedure. The null hypothesis was that the two-step application of either MRBS or BRBS would not result in different dislocation resistance values compared to their single-step application procedure.

**MATERIALS AND METHODS**

**Tooth Selection and Preparation**

Eighty recently extracted single-rooted human teeth (excluding mandibular incisors) stored in water at room temperature were selected. Radiographs were taken. Inclusion criteria included the presence of a single straight (<10 degrees, Weine method) untreated root canal; the absence of root caries, resorption, and calcification; and complete apex formation. The mesio-distal and bucco-lingual thickness of each root was measured with calipers at 5 mm from the apex in order to achieve homogeneity of root bulk distribution among the 4 different groups (n = 20/group). An axial section was performed in order to standardize the roots lengths to 15 mm. All specimens were prepared and obturated by a single operator. A size 10 K-file (Dentsply Maillefer; Ballaigues, Switzerland) was placed inside the canal and moved apically until it was just visible at the apical foramen. Apical patency was verified at the beginning and at the end of the procedure. Working length (WL) was determined by subtracting 1 mm from this length. Files of ascending size were consecutively brought to working length starting from size 20, taper 0.06, to size 40, taper 0.06, with nickel-titanium instruments (Mtwo, VDW; Munich, Germany) using a torque-control motor (VDW Silver, VDW). Irrigation was performed with 2 ml of 2\% NaOCl (Denteck, IL Zoe-termeer; the Netherlands) between each file and delivered with a 27G open-ended needle (Neolus NN-27.19R, Terumo Europe; Leuven, Belgium) placed slightly short of WL. A final rinse with 3 ml of 17\% EDTA (Vista Dental Products, Inter-med; Racine, WI, USA) for 2 min was followed by a 3-ml rinse of distilled water. The canals were then dried with paper points and filled.

**Root Canal Filling**

Root canal filling was conducted as described below and illustrated in Fig 1.

- Group 1, MRBS 2-step placement (n = 20): RealSeal SE (RS) sealer was placed in two steps. The sealer was placed in the root canal by means of a 2.5-ml syringe (Terumo; Tokyo, Japan) and a capillary tip (Ultradent Products; South Jordan, UT, USA) placed 3 mm from WL and gently withdrawn during sealer delivery. A size 25 EZ-Fill bi-directional spiral (EDS; S. Hackensack, NJ, USA) was rotated at 300 rpm for 5 s at 3 mm from WL. A size 40, 0.06 taper custom-made polyoxymethylene cone (SKM Rapid Modelling; Helmond, the Netherlands) was inserted in the canal to WL to increase the unbonded surface of the sealer in order to decrease the C-factor. Polyoxymethylene is an inert material that does not react with the sealers used in this study. The specimens were stored at 37\degree\textsuperscript{C} and 100\% humidity for 1 week to allow the sealers to set. After 1 week, the polyoxymethylene cone was easily pulled out of the canal, fresh sealer was placed as previously described and an RS cone size 40, 0.06 taper was placed in the canal to WL.
- Group 2, MRBS 1-step placement (n = 20): RS sealer was placed in one step in the root canal by means of...
FIG 1 Schematic representation of the conducted protocol. 80 roots were standardized and divided into 4 groups. After root canal preparation, obturation was conducted either with a two- or one-step technique. After sealer setting, 1-mm-thick slices were cut at 3, 6, and 9 mm from the apex. Each slice was tested in an apico-coronal direction with the push-out test and the resistance to dislocation was calculated. Inert cone: standardized polyoxy-methylene cone. MRBS: methacrylate resin-based root canal sealer (RealSeal SE). RS-cone: RealSeal cone, dimethacrylate-containing polycaprolactone-based thermoplastic cone. BRBS: bisphenol epoxy resin-based root canal sealer (AH Plus). GP-cone: Mtwo gutta-percha cone.

A 2.5 ml syringe and a capillary tip placed 3 mm from WL and gently withdrawn during sealer delivery. A size 25 EZ-Fill bi-directional spiral was rotated at 300 rpm for 5 s at 3 mm from WL. An RS cone size 40, 0.06 taper was placed in the canal to WL.

- Group 3, BRBS 2-step placement (n = 20): Root canals were obturated with AH Plus sealer and a single Mtwo gutta percha cone size 40, 0.06 taper (VDW) according to the same protocol as in group 1.
- Group 4, BRBS 1-step placement (n = 20): Obturation was conducted with AH Plus sealer and a single Mtwo gutta percha cone size 40, 0.06 taper according to the same protocol as in group 2.

Subsequently, all specimens were stored at 37°C and 100% humidity for 1 week to allow the sealers to set.

Dislocation Resistance by Push-out Testing and Failure Mode

Each specimen was placed vertically in a standardized plastic mold and was embedded in self-curing polymethyl methacrylate resin (PMMA) (Vertex self-curing, cold-curing acrylic, Vertex Dental; Zeist, the Netherlands). After the acrylic resin set, each specimen was sectioned perpendicular to its long axis with a low-speed water-cooled diamond disk (Leica SP1600; Wetzlar, Germany) to yield 1-mm-thick slices at 3, 6, and 9 mm from the apex, referred to as the apical, middle and coronal sections (n = 240). The thickness of the saw (0.3 mm) was taken into account during this process. Each slice was marked on its apical surface. The root slices were then dislodged from the embedding material and digital precision calipers (Model 500-144, Mitutoyo; Kawasaki, Japan) were used to measure the exact thickness of each slice. The diameters of the canal on the coronal and apical aspects of each slice were measured using a Zeiss Stemi SV stereoscopic microscope (Carl Zeiss Microscopy; Göttingen, Germany) and the AxioVision software (Carl Zeiss). For each slice the diameter was calculated as follows. Since the canals rarely have perfect circularity, the largest diameter D1 was measured. Then the longest diameter perpendicular to D1 was also measured; this was D2. The diameters D1 and D2 were averaged and the result corresponded to the considered diameter of the canal.

Each slice was then placed in a universal testing machine (Instron 6022, Instron; Canton, MA, USA) on an epoxy plate with orifices of different diameters. For each slice, an orifice with a diameter smaller than that of the slice but larger than that of the diameter of the canal was chosen. Three cylindrical stainless-steel punchers with corresponding diameters of 0.3, 0.5, and 0.8 mm, were used. For each slice, the puncher that could cover as much of the root canal filling without touching the root canal wall was chosen. The puncher was advanced at a rate of 0.5 mm/min in an apico-coronal direction until the root canal filling was dislodged, which was established by the appearance of a sudden drop of the load/time curve recorded by the universal testing machine monitor. For each section, the dislocation resistance value DR (MPa) was obtained by dividing the failure load F (N) by the interface area (mm²) between the root canal filling and dentin. The tested sections corresponded to a truncated cone, and dislocation resistance was calculated in Excel 2010 (Microsoft; Redmond, WA, USA) as:

$$DR = \frac{F}{\pi(r+R)s}$$

where the slant height is $s = \sqrt{(R-r)^2 + h^2}$ with R and r being the radii of the bases of the frustum and h the slice thickness (in mm).

After the push-out test, all the slices were examined with a Zeiss Stemi SV stereoscopic microscope at 50X magnification to determine the failure mode, which was...
classified as follows: adhesive between the cone and the sealer; cohesive within the sealer; adhesive between the sealer and dentin; mixed (adhesive and cohesive); cohesive within dentin; cohesive within the cone.

**Scanning Electron Microscopy (SEM)**
Randomly selected untested slices from the MRBS groups were mildly air dried, and impressions of the cut surfaces were obtained using a vinyl polysiloxane impression material (Flexitime Correct flow and Flexitime Heavy Tray, Heraeus Kulzer; Hanau, Germany). Replicas of the slices were fabricated using a self-curing epoxy material (Araldite DRL and Hardener, Ciba Geigy; Groot-Bijgaarden, Belgium). The replicas were mounted on aluminum stubs, gold-sputtered, and examined with an SEM (XL-20, Philips, Eindhoven; the Netherlands) at 80X and 250X magnification to visualize the MRBS behavior in the one- and two-step procedures. The use of an indirect method for scanning was favored over a direct one in order to avoid potential damage to specimens due to over drying.

**Phase-contrast–enhanced Micro-CT**
Two untested MRBS segments were scanned for 3D imaging using phase-contrast–enhanced micro-CT on BAMline of the HZB BESSY-II storage ring (Helmholtz Zentrum Berlin, Germany). The slices, still embedded in PMMA, were mounted on the CT rotation stage and imaged using a monochromatic beam at an energy of 30keV using the beamline imaging system set to an effective pixel size of 4.348 μm and a small propagation distance of 25 mm. The 1500 radiographs were normalized and reconstructed using the public-domain ESRF software package PyHST.

**C-factor Determination**
The C-factor calculation was conducted to illustrate the benefits of the two-step procedure. The filled root canal in the present study can be modelled as an inverted cone of apical diameter 0.40 mm, taper 0.06, and height = 15 mm. With all the physicochemical properties of the materials considered as remaining constant, the C-factor is defined as:

\[
\text{C-factor} = \frac{\text{Bonded area (in mm)}^2}{\text{Unbonded area (in mm)}^2}
\]

**Statistical Analysis**
The interface areas and the dislocation resistance values did not follow a normal distribution as determined by the Shapiro-Wilk test; therefore, non-parametric tests were used. Comparisons between groups 1 and 2 and between groups 3 and 4 at the same root levels were made with the Mann-Whitney U-test. Different cross sections within the same group were compared with the Friedman test. The interface areas were compared between the different groups using the Kruskal-Wallis test in order to verify dimensional homogeneity among them. The level of significance was set at p = 0.05. Statistical analyses were performed using SPSS version 21 (SPSS; Chicago, IL, USA).

**RESULTS**

**Dislocation Resistance and Failure Mode**
The median dislocation resistance values with the interquartile ranges are summarized in Tables 1 and 2. Effect sizes for the pairwise comparisons were reported as absolute values of Pearson’s correlation coefficient r.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Dislocation resistance (in MPa) in the MRBS groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root level</td>
<td>MRBS 2-step</td>
</tr>
<tr>
<td>Coronal</td>
<td>2.28 (1.58–3.29)</td>
</tr>
<tr>
<td>Middle</td>
<td>2.82 (1.64–4.23)</td>
</tr>
<tr>
<td>Apical</td>
<td>3.14 (2.54–5.71)</td>
</tr>
<tr>
<td>p-values (Friedman rank test)</td>
<td>0.086</td>
</tr>
</tbody>
</table>

Values are expressed as median (interquartile range). p < 0.05 significant.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Dislocation resistance (in MPa) in the BRBS groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root level</td>
<td>BRBS 2-step</td>
</tr>
<tr>
<td>Coronal</td>
<td>0.95 (0.42–1.66)</td>
</tr>
<tr>
<td>Middle</td>
<td>1.32 (0.72–2.48)</td>
</tr>
<tr>
<td>Apical</td>
<td>1.05 (0.52–2.89)</td>
</tr>
<tr>
<td>p-values (Friedman rank test)</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

Values are expressed as medians (interquartile range). p<0.05 significant.
The interface areas were not significantly different among the different groups ($p = 0.32$), meaning that the tested surfaces were comparable from a dimensional point of view.

At each root level, the dislocation resistance values were significantly higher for the two-step than for the one-step procedure for the MRBS ($p = 0.003$, $p = 0.005$, $p < 0.001$) (Table 1), while no significant differences were found for the BRBS at any of the 3 root levels ($p = 0.83$, $p = 0.1$, $p = 0.06$) (Table 2), meaning that a two-step procedure increased the dislocation resistance of MRBS but not of BRBS.

Dislocation resistance values were significantly different between the three root levels in groups 2, 3, and 4 ($p < 0.001$, $p < 0.001$, $p = 0.015$) (Tables 1 and 2), illustrating varying dislocation resistance of the filling material along the root canal. In group 1 (Table 1), dislocation resistance did not differ significantly between all tested root levels ($p = 0.086$), reflecting a more homogeneous dislocation resistance along the root canal.

Failure mode analysis (Table 3) revealed that the failure was mainly mixed (76% and 52%, respectively) in groups 1 and 2, indicating a complex response to push-out tests. In groups 3 and 4, the failure was mainly adhesive between the sealer and the cone (85% in both groups), reflecting the weak adhesion between gutta percha and BRBS.

**SEM**

SEM examination revealed that two distinct MRBS layers can clearly be identified in the specimens of group 1 (Figs 2 and 3). The first MRBS layer seems to adhere homogeneously to dentin, while the second layer has a more heterogeneous aspect. Gaps were clearly visible at the junction between dentin, the RS cone, and the MRBS in group 2 (Fig 4).

**Phase-contrast–enhanced Micro-CT**

The phase-contrast–enhanced micro-CT reconstructions reveal examples of the relative dimensions and geometries of the cone, sealer, and canal wall in the one and two-step MRBS samples. They indicate the existence of a gap between the sealer and the RS cone in both MRBS groups (Figs 5 and 6). However, the MRBS seems more evenly distributed within the root canal in group 1 (two-step placement) (Fig 5) than in group 2 (one-step placement), where a thicker gap on one side is seen (Fig 6).

### Table 3  Failure mode (%) for all groups after push-out testing

<table>
<thead>
<tr>
<th>Group</th>
<th>Failure mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRBS 2-step</td>
<td>18</td>
<td>0</td>
<td>4</td>
<td>76</td>
<td>0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>MRBS 1-step</td>
<td>39</td>
<td>2</td>
<td>5</td>
<td>52</td>
<td>0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>BRBS 2-step</td>
<td>85</td>
<td>0</td>
<td>7</td>
<td>7</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>BRBS 1-step</td>
<td>85</td>
<td>9</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Failure mode categories: adhesive between the cone and the sealer (1), cohesive within the sealer (2), adhesive between the sealer and dentin (3), mixed (adhesive and cohesive) (4), cohesive within dentin (5), and cohesive within the cone (6).
C-factor

If we consider the shape of the root canal to be a cone of height $h$, slant height $L$, and radius of the base $R$, then its lateral surface, which corresponds to the bonded area, will be:

$$\text{Bonded area} = \pi RL$$

The unbonded area corresponds to the sealer layer’s axial area at the coronal aspect of the canal between the dentinal wall and the RS cone. It is the difference between a discus of radius $R$ and one of radius $R - r$, as it is a crown of width $r$ at the circumference inside the former discus. The unbonded area is therefore

$$\text{Unbonded area} = \pi R^2 - \pi (R - r)^2 = \pi r (2R - r)$$

The C-factor corresponds to the ratio:

$$\text{C-factor} = \frac{\text{Bonded area}}{\text{Unbonded area}}$$

and is therefore given by the equation:

$$\text{C-factor} = \frac{LR}{r (2R - r)}$$

with

$$\lim_{r \to 0} \text{C-factor} = \infty$$

and

$$\lim_{r \to R} \text{C-factor} = \frac{L}{R}$$

The thinning of the MRBS layer ($r \to 0$) would result in an increase of the C-factor, whereas filling the whole root canal only with sealer ($r \to R$) would result in a C-factor of:

$$\frac{\sqrt{R^2 + h^2}}{R} = \frac{\sqrt{1.69 + 225}}{1.3} = 11.58$$

The use of a two-step placement procedure allows controlling the C-factor for the first sealer layer. Indeed, when placed with the polyoxymethylene cone, the unbonded surface is:

$$\text{Unbonded area} = \pi RL + \pi r (2R - r)$$

with the bonded surface being:

$$\text{Bonded area} = \pi RL$$

Therefore:

$$\text{C-factor} = \frac{RL}{RL + r (2R - r)}$$

Considering the most unfavorable situation with $r = 0$, the equation becomes:

$$\text{C-factor} = \frac{RL}{RL} = 1$$

Considering the most favorable situation with $r = R$, the equation becomes:

$$\text{C-factor} = \frac{L}{L + R} < 1$$

**DISCUSSION**

The purpose of the present study was to investigate whether the placement of a MRBS or a conventional BRBS in two steps increases their dislocation resistance when compared to a one-step placement procedure. The two main findings of the present study were
an increase in dislocation resistance and a decrease in its variability along the entire root canal length when the MRBS was placed in two steps as compared to one. Conversely, no difference could be detected in dislocation resistance between the one- and two-step procedures with the BRBS sealer used as control.

Our results are in line with those of the study of Bouillaguet et al.,3 in which a resin-based adhesive cement intended for crown restoration was used as a root canal sealer. Using restorative cements as the authors did is clinically possible, but may complicate retreatment procedures.

In the present study, the two-step placement of the MRBS was achieved by using a cone made of polyoxymethylene, an inert material, in the presence of the sealer. Polyoxymethylene has no chemical reactivity and is therefore unlikely to allow adhesion if polished.17 Its removal is easy to achieve by pulling its free coronal extremity out of the canal, without any cement adhering to its surface. When the first layer of sealer is applied and the polyoxymethylene cone put into place, the surface of the sealer in contact with the polyoxymethylene cone is an unbounded surface. The lower C-factor compared to a single-step procedure reduces polymerization stress within the first layer of the sealer and allows better adhesion of the sealer to the root canal dentin.25 The second sealer layer placed with the RS cone is much thinner and its volumetric shrinkage is consequently reduced, which in turn is expected to reduce shrinkage stress. The remarkable difference detected in this study between the one- and two-step placements of the MRBS illustrates the importance of the cavity configuration for adhesion inside root canals. While during the one-step procedure the polymerization shrinkage may provoke the detachment of the sealer from dentin or from the RS cone, in the two-step procedure, the first layer of sealer could freely shrink towards dentin. The shrinkage of the second layer may have little influence on the dislocation resistance because it is relatively thin.14

Another finding of the present study was reduced variability in dislocation resistance among root levels in group 1 (MRBS two-step procedure) as opposed to all the other groups, in which the dislocation resistance was found to be heterogeneous among root levels. Contradicting results have been reported regarding dislocation resistance at different root canal levels.6,24 Methodological diversity in combination with anatomic variability and the fact that the stress applied to the material during the push-out test is not evenly distributed on the root canal wall may partly explain these differences.14 Remarkably, the effect of the root canal level on dislocation resistance disappeared in the MRBS two-step group. The first layer of sealer may have standardized the shape of the canal to the shape of the obturation cone by flowing more freely while setting and adhering to root canal dentin. As a result, the adhesion along the entire root canal was homogenised.14 This was confirmed by the phase-contrast–enhanced micro-CT images which revealed a more homogeneous distribution of the sealer within the root canal (Fig 5). To the best of our knowledge, the present study is the first to use micro-CT to demonstrate gaps between MRBS and the obturation cone within the root canal. The presence of these gaps had until now only been described with SEM on resected root surfaces. It is assumed that these gaps result from the severe polymerization shrinkage MRBS undergo in cavities with a high C-factor.19

Interestingly, in contrast to the MRBS groups, there were no differences in dislocation resistance between the one- and two-step procedures for the BRBS. This could be explained by the lower polymerization shrinkage that BRBS undergo compared to MRBS. Their molecular structure and their polymerization pattern make BRBS less prone to polymerization shrinkage compared to MRBS. At the molecular level, the lower overall crosslink density in the BRBS bisphenol epoxy molecules compared to the methacrylates present in MRBS limits the extent of crosslinking and thus polymerization shrinkage.18 Epoxy molecules contain an oxirane ring. During the polymerization process, ring opening lowers shrinkage, while the delayed consumption of the reactive species could provide stress relaxation.11 Furthermore, BRBS polymerize by polyaddition of diglycidyl ether of bisphenol-A and a di-secondary diamine,16 whereas MRBS polymerize by condensation polymerization. Polymerization by condensation is more subject to shrinkage than polymerization by polyaddition.26 In the present study, the fact that the dislocation resistance of the BRBS was not influenced by the number of layers suggests that the increase in dislocation resistance observed in the MRBS two-step group could be attributed to a decrease in polymerization stress rather than simply to the presence of two sealer layers.

The advantage of the push-out test is that it evaluates materials which have set in cavities, presenting a C-factor corresponding to the clinical situation.23 It measures a combination of forces which resist the dislocation of the tested material. In addition to the bond strength of the tested material, a frictional component, which is influenced by the material’s elastic modulus, plays a significant role.4,5,10,23 Consequently, no attempt was made in the present study to compare the results of groups 1 and 2 with those of groups 3 and 4, since MRBS and BRBS as well as gutta-percha and RS cones have different elastic moduli.

BRBS do not have the ability to adhere to the polyisoprene composing gutta-percha.9 This was confirmed by the high percentage of adhesive failure observed at the interface between gutta-percha and the BRBS in groups 3 and 4. The weak adhesion between MRBS and dentin as well as between MRBS and the dimethacrylate-containing polyester-based cones has already been demonstrated.9 The low concentration of dimethacrylates and the absence of free radicals within the RS cone may explain the weak bond between the RS cone and the BRBS. Furthermore, the already weak adhesion between MRBS and dentin could be weakened further by stress concentrators corresponding to locations with geometric discontinuity within the material.9 Jongsma et al.14 investigated the contraction stress occurring during post cementation with one- and two-step procedures by means of finite element analysis. They found that even though the maximum stresses were mainly located within the cement layer, they also propagated deeply into dentin and the post. This illustrates
the complexity of the polymerization stress pattern and could clarify the relatively high proportion of mixed failure observed in the MRBS groups.

The C-factor calculation revealed that with a two-step procedure, the C-factor could be maintained below a value of 1 within the first layer. In comparison, during a single-step procedure, the C-factor could not go below a value of 11.58, considering the dimensions of the investigated root canals. In comparison, the second sealer layer would polymerize in an environment with an extremely high C-factor. However, despite the high shrinkage stress that the second layer would endure, its thin width would limit its relative volumetric shrinkage and therefore its influence on the dislocation resistance values.

Despite the improvement in dislocation resistance of the MRBS when a two-step procedure was used, currently available root canal sealers present extended setting times, which prevents clinical application of this technique without the use of accelerators. Nevertheless, the results of this study may be considered as a proof of concept and serve as a motive for the development of alternative root canal filling strategies with faster-setting MRBS sealers or the additional use of accelerators.

CONCLUSION

Reducing the C-factor by layering the root canal sealer with a two-step procedure resulted in significantly higher dislocation resistance values compared to a single-step procedure for a methacrylate resin-based sealer but not for a conventional bisphenol epoxy-resin-based root canal sealer.

ACKNOWLEDGMENTS

We gratefully acknowledge the help of Mr. Arie Werner for technical support and operating the scanning electron microscope, Dr. Christos Boutsioukis for thoughtful review of the manuscript, Dr. Paul Zaslansky for helpful suggestions and his contribution with the phase-contrast enhanced micro-CT images, and The Helmholtz-Zentrum Berlin (HZB) for the allocation of synchrotron radiation beamtime.

REFERENCES


Clinical relevance: A two-step root filling procedure with a methacrylate sealer demonstrated a highly significant increase of its adhesion ability to root canal dentin. The development by manufacturers of faster setting sealers or the additional use of accelerators could make this technique clinically applicable and would represent a simple way to improve the quality of the root canal filling.