Title

In vitro fracture strength and patterns in root filled teeth restored with different base materials.

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Conflict of Interest

The authors certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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Abstract

Title: Fracture strength and patterns in root filled teeth restored with different base materials.

Background: There is little research on the effects of an intermediate base on the fracture strength of root filled teeth. This study compared the fracture strengths and patterns of root filled teeth restored with intermediate bases of GIC, ZPC, DCRC and Biodentine® under resin composite.

Methods: Standardised cavities were prepared in 100 extracted human maxillary and mandibular premolars, and root canal treatment was performed. The teeth were stratified and randomly allocated to five groups (n = 20): 1. GIC; 2. ZPC; 3. DCRC; 4. Biodentine®; and 5. Prepared but unrestored (control). The teeth were subjected to an oblique, ramped load until fracture. The fracture loads, level, mode and location were recorded.

Results: Mean fracture strengths of all restored groups were not significantly different amongst the groups. There were significant overall effects on mean fracture strength for tooth type (P = 0.002) and bucco-lingual width of the crown (P = 0.001).

Conclusions: The four materials were appropriate intermediate bases. The laminate restorative technique promoted fracture strengths that are likely to withstand normal and maximum masticatory function. The base material can influence failure mode, which may have implications for the clinical presentation of fractures of root filled teeth.

Introduction

Preservation of remaining coronal structure and the use of adhesive restorative materials have been recommended in restoring root filled teeth.[1,2] *In vitro* studies have shown that RFT restored with resin composite have significantly higher fracture resistance values than unrestored teeth or root filled teeth restored with amalgam.[1, 3,4] Clinical studies have reported lower fracture rates of root filled teeth restored with direct resin composite when compared with other direct restorations and comparable fracture rates to cast restorations.[5,6] Long-term survival rates of root filled teeth restored with resin composite have been reported to be 85%[7], with some studies showing comparable short-to-medium-term survival rates with root filled teeth restored with crowns.[8,9]

The incorporation of an intermediate base under the resin composite reduces the bulk of resin composite, which lowers the volume of available resin monomer for conversion, leading to reduced shrinkage stress[10-12] and better bond strengths.[13] A base contributes to more uniform stress distribution and strain values within the tooth-restoration complex under functional load.[14, 15] Further, a base can confine resin-dentine bonding to more superficial dentine, which has more favourable microstructure and mechanical properties for better bond strength and durability.[16]

Traditional and contemporary restorative materials that can be used as bases or cores include acid-base dental cements, such as GIC and zinc polycarboxylate cement (ZPC), and resin-based cores. Conventional GIC is a commonly used restorative material that chemically bonds to tooth structure via ionic exchange[17] and is a suitable base material because it has very little shrinkage and less microleakage than resin composites.[18] ZPC belongs to the same class of materials as GIC and has similar bonding and mechanical properties.[19] Dual-cured resin composites (DCRCs) were developed to overcome the limitations of both photoactivated resin composites , which suffer inadequate light-curing in deep areas, and self-cure resin composite, which have prolonged setting time as well as inferior mechanical properties and bond strengths.[20]

A calcium silicate-based restorative material, Biodentine®, has been marketed as a dentine replacement material and recommended as a base under permanent restorations.[21] The available literature on the laboratory and clinical performance of Biodentine® as a restorative base material has provided support for its use as a restorative base.[22-24]

Currently, there is a deficiency of research on the effects of an intermediate base under a direct resin composite on the fracture strength of root filled teeth. Therefore, the aim of this study was to determine and compare the fracture strengths and patterns of root filled teeth, directly restored with intermediate bases, using GIC, ZPC, DCRC and Biodentine® under resin composite.

Materials and Methods

Tooth selection

One hundred intact human permanent maxillary and mandibular premolars, extracted for orthodontic reasons, were collected and stored in 1% chloramine T solution (pH 7.8) with the patients' informed consent and approval by the Ethics in Human Research Committee (Ethics ID no. 1340577). Collected teeth were inspected under magnification (8x) to eliminate those with caries, previous restorations, cracks or fractures.

Access cavity preparation and root filling

The following measurements were recorded for each tooth using a digital caliper (Craftright Engineering Works, Jiangsu, China): buccolingual (B-L) and mesiodistal (M-D) widths of the crown (at the maximum convexity), the crown height (measured from the buccal cusp tip to the cemento-enamel junction [CEJ] buccally) and tooth length (measured from the highest cusp tip to the lowest root apex). For each tooth, a standardised mesio-occlusal-distal (MOD) cavity was prepared using a high-speed diamond bur (Komet Horico 199-014; Brasseler, Lemgo, Germany). The B-L width of the proximal boxes was one-third of the B-L width of the crown, the B-L width of the occlusal isthmus was one-half of the intercuspal width, and the gingival floor was 2mm coronal to the CEJ. The cavosurface margins were prepared at 90° perpendicular to the long axis of the tooth with rounded internal angles. An access cavity was then cut through the pulpal floor of the cavity and extended to completely expose the pulp chamber and to allow straight-line access to the canals.

The root canals were instrumented using Mtwo® (VDW, Munich, Germany) rotary nickel-titanium (NiTi) instruments and obturated by cold lateral compaction of gutta percha and epoxy-resin root canal sealer (AH Plus® Jet™; Dentsply, Maillefer DeTrey, Konstanz, Germany) to 1 mm below the gingival floor of the MOD cavity. The teeth were wrapped in moist gauze and stored in individual vials under normal room temperature and humidity for at least seven days to allow the sealer cement to set.

Randomisation and group allocation

A total of 55 maxillary premolars and 45 mandibular premolars were selected and randomly assigned to the five groups so that each group contained 11 maxillary and 9 mandibular premolars. For each tooth, a volumetric value based on the crown was calculated by multiplying the B-L width, M-D width and crown height. For stratification purposes, the teeth were then arranged according to tooth type (maxillary or mandibular premolar) and volumetric value in an ascending order. A hundred random integers were generated using a random number generator (https://www.random.org/integers/) and each integer was assigned to the ordered teeth. The teeth were then divided into blocks of five and the specimens within each block were then ordered in ascending order (from one to five) according to the assigned integer and allocated to the following groups. The restorative materials used are listed in Table 1 and all were used according to the manufacturers' instructions.

Group 1: Glass ionomer cement (GIC) base with resin composite restoration (n=20)

The dentine surfaces of the cavity were conditioned with Ketac™ Conditioner for 10 seconds. After rinsing the cavity and air-drying with a triplex spray, a base of GC Fuji IX™ GP was placed within the cavity. The GIC was left to set for 15 minutes before being trimmed with a diamond cylinder flat-tip bur under water-cooled conditions (Komet Horico 110-012; Brasseler, Lemgo, Germany) so that it was 1 mm within the M-D cavity margins and 1.5 mm below the occlusal surface.

The enamel and dentine of the cavity walls were then cleaned under a microscope (Möller SPECTRA 500; Möller-Wedel, Wedel, Germany) to ensure that the surfaces were free of GIC before being prepared using the dentine bonding system. The cavity was then restored with resin composite with each increment being cured for 20 seconds using a light curing unit (Radii Plus; SDI Ltd, Bayswater, Australia), which has a peak light intensity of 1,200 mW/cm^2. The restoration was then shaped and polished with a diamond polishing bur (Komet 368-023; Brasseler, Lemgo, Germany) and finishing cup (Enhance® Finishing System; Dentsply, Konstanz, Germany). The teeth were handled in moist gauze during all restorative procedures to prevent dehydration, then wrapped in moist gauze and stored within individual vials for two weeks.

Group 2: Zinc polycarboxylate cement (ZPC) base with resin composite *restoration (n=20)*
The specimens were prepared and restored as in Group 1 but with ZPC as a base material. Durelon™ was mixed and delivered into the cavity using a flat paste-filler (FKG Dentaire, La Chaux‑de‑Fonds, Switzerland).

Group 3: Biodentine base with resin composite *restoration (n=20)*
The specimens were prepared and restored as in Group 1, except without conditioning of the cut dentine surfaces and with Biodentine® as a base material. The Biodentine® base was allowed to set for 15 minutes.

Group 4: Dual-cure resin core (DCRC) base with resin composite *restoration (n=20)*
The cut dentine surfaces of the cavity were prepared with LuxaBond® Total Etch and LuxaCore® Dual was placed as a base, light-cured for 40 seconds and left to set for 15 minutes. The specimens were then prepared and restored as in Group 1.

Group 5: Unrestored group (n=20)
The teeth within this group were left unrestored after cavity preparation and root filling, and served as negative controls.

Tooth mounting
The external root surfaces of all teeth were painted with a thin layer of silicon impression material (Aquasil™ Ultra XLV Fast Set; Dentsply, Milford, USA) of 0.2-0.3 mm in thickness (verified with the digital caliper) using a bristle brush to simulate a periodontal ligament (PDL). The teeth were then positioned within cylindrical mounting vessels, which were cut from electrical conduits, and secured with a thin strip of border wax such that the long axis

of the tooth was parallel to the walls of the conduit. Acrylic resin (Vertex™ Self-Curing; Dentimex, Zeist, Netherlands) was mixed and poured into the conduit to mount the tooth at approximately 1 mm apical to the CEJ (Fig. 1). Once set, the mounted teeth were immersed in a water bath until complete curing, then stored in 100% humidity at 37°C until testing.

Fracture strength test and evaluation of fracture patterns

Prepared specimens were randomly selected and subjected to an oblique, ramped load until fracture. The load was applied at 45° to the long axis of the tooth on the lingual/palatal incline of the buccal cusp, at a rate of 0.5 mm/min, in an Instron testing machine (model 5544 series; Instron Corp., Canton, MA, USA) using a rounded steel loading tip measuring 2.65 mm in diameter. Loading forces to tooth fracture were recorded in Newtons (N). All specimens were examined under magnification to evaluate the fracture patterns. These were categorised according to the restoration-tooth interface at which the fracture occurred (buccal or lingual) and the level of fracture relative to the CEJ (above, at, or below CEJ).

Scanning electron microscope (SEM)

Both fragments of each specimen were examined under the SEM (Quanta FEG 200 ESEM; FEI, Oregon, USA) at various magnifications (50-1000x) to determine the modes of failure for the resin composite and base materials. The classifications for failure modes (Tables 2 and 3) were modified from previous criteria.[39-43] Two classifications were used because of the different tooth structure involved at the restoration-tooth interface (enamel for resin composite and predominantly dentine for the bases).

Statistical analysis

The fracture loads were analysed using one-way analysis of variance (ANOVA), with statistical significance defined as a two-sided P-value of less than 0.05, using statistical software (SPSS 22 for Windows, SPSS Inc., Chicago, IL, USA). Chi-squared and Fisher's exact tests were used to analyse the fracture loads as well as the level, location and mode of fracture. All statistical analyses were performed at the 95% level of confidence.

Results

One-way ANOVA showed no significant differences among the groups with regard to tooth dimensions.

Fracture strength

Analysis of variance tested interactions between the treatment groups and tooth type or tooth dimensions, but they were not found to be significant and were therefore excluded from the model.

Table 4 shows the mean fracture strengths for the five groups, averaged over all other factors. There was a highly significant difference in mean fracture strengths between the control and all experimental groups ($P < 0.001$), but no significant differences between any restored groups.

Mandibular premolars had a significantly higher mean fracture strength than maxillary premolars (408N vs 318N, $P = 0.002$). For each millimetre increase in B-L crown width, the fracture strength of the tooth increased by 73N ($P = 0.001$). There were no significant effects of M-D width, crown height or tooth length on mean fracture strength regardless of tooth type.

Fracture patterns

Fractures occurring at or above the CEJ (Table 5) were grouped together to represent 'favourable' fractures (51.3%), and fractures below the CEJ were classified as 'unfavourable' (48.7%). There was no significant association between the proportions of favourable or unfavourable fractures and the treatment group or tooth type, with or without the control group included in the analysis.

The majority of specimens fractured at the buccal restoration-tooth interface for all restored groups. Excluding the control group, a significantly greater number of fractures occurred at the lingual restoration-tooth interface in the DCRC group when compared with the other treatment groups ($P = 0.035$). No significant association was found between tooth type and the location of the fracture interface.

Failure mode

Most specimens displayed mixed failure with predominantly adhesive failure and minor cohesive failure of the resin composite (Table 6) but there were no significant differences between any treatment groups.

None of the samples in the four experimental groups showed pure adhesive or cohesive failure of the base material (Table 6). The modes of failure were significantly different among the different base materials: GIC vs ZPC ($P < 0.001$), GIC vs Biodentine ($P < 0.001$), GIC vs DCRC ($P < 0.001$), ZPC vs Biodentine ($P < 0.001$), ZPC vs DCRC ($P < 0.001$), except for the Biodentine and DCRC groups, both of which displayed similar modes of failure. Figure 2 shows typical appearances under high magnification (x1000) of the SEM that illustrate the failure modes unique to each of the four base materials.

Discussion

Limitations of fracture studies

Laboratory settings do not adequately mimic normal intraoral conditions in which teeth are immersed in an aqueous environment and subjected to complex masticatory forces as well as chemical and thermal challenges that can influence fracture resistance of teeth.[25,26] However, such studies are useful in assessing fracture toughness and fracture patterns of teeth, and to help understand the behaviour and failure of the tooth-restoration complex under specific functional conditions.[27, 28]

Fracture strength

Restoration with bonded direct resin composite and different bases significantly increased the fracture strength of root filled teeth compared with unrestored root filled teeth, which corroborated other studies.[1,3,29]

The use of restorative materials with moduli of elasticity similar to dentine has been recommended to improve the stress-strain relationship and fracture strength of restored teeth.[30] While the elastic moduli of resin composites (including DCRC) are similar to dentine[31] and much higher than GIC, ZPC and Biodentine®,[32-34] there was no significant difference in the mean fracture strengths among the restored groups in the present study. It is possible that the direction and location of loading, rather than the elastic modulus itself, had a greater impact on the resultant stress-strain distribution within the tooth-restoration complex and subsequent fracture initiation and propagation.

Comparison of fracture strengths with normal and maximum occlusal forces

The mean fracture strengths of all four restored groups were more than 100N higher than the reported range of functional chewing forces of 24N to 262N.[35-39] The maximum bite forces exerted on premolars are in the range of 179-400N[39] and so the mean fracture strengths of all of the restored groups in the present study compared favourably with these data. Further, because the mean fracture strengths of root filled teeth are significantly higher with compressive axial loading rather than oblique loading,[40] the compressive fracture strengths of all the restored groups in the present study (loaded at 45°) would likely be above the maximum reported biting forces for premolars.

Effects of tooth factors on fracture strength

The B-L dimension of the crowns was significantly associated with fracture strength, which is logical given that loading was applied in the B-L direction and the widths of the MOD cavities were prepared in proportion to the B-L dimension. The buccal cusps of crowns with greater B-L widths would thus have greater residual B-L thicknesses leading to greater fracture toughness.[4,41]

Maxillary premolars had lower mean fracture strength than mandibular premolars, which is probably due to the differences in crown anatomy. Thus, the MOD cavities in mandibular premolars would be positioned more lingually when compared with maxillary premolars. Therefore, for a maxillary and mandibular premolar with the same B-L crown width, the residual B-L thickness of the mandibular premolar would be greater than the maxillary premolar after preparation of a standardised MOD cavity.

Level of fracture

The proportions of 'favourable' and 'unfavourable' fractures were similar among the restored groups, which agreed with some studies[42,43] but not with others in which most restored root filled teeth fractured at 'subcrestal', 'unrestorable' or 'unfavourable' levels.[1,34,44] These differences in findings may be attributed to the different cavity dimensions, loading conditions, materials used for the mounting of teeth as well as the simulation of the PDL. PDL simulation may not significantly influence the maximum ramped load to fracture but the fracture location can be significantly affected.[45]

Fracture interface

Significantly more specimens in the DCRC group failed at the lingual restoration-tooth interface when compared with the other three restored groups. The higher mechanical strengths and plastic deformation of LuxaCore® may allow it to resist fracture and even exceed its tensile bond strength to dentine at the lingual restoration-tooth interface, thus leading to these teeth failing at the lingual restoration-tooth interface. Further, the similar mechanical properties of resin composite and LuxaCore®, as well as the bond strength between these two materials, may have contributed to a better stress-strain distribution within the resin composite-LuxaCore® restorative complex, with the resultant stress concentrating at the lingual restoration-tooth interface and leading to fracture at the resin-dentine interface.

Mode of failure

Differences in the failure mode of the base materials may have implications on the clinical presentation of root filled teeth when fracture of the tooth-restoration complex occurs. For example, adhesive failure of a base material may lead to propagation of the fault along the adhesive interface that then extends obliquely beneath the loaded cusp as a restorable cuspal fracture. In contrast, cohesive failure within the base may result in unfavourable stress-strain concentration in the centre of the tooth and extension of a coronal crack-line apically, which may potentially lead to a more catastrophic fracture of the root filled teeth.[1]

Under the SEM, the fractured surfaces displayed characteristic patterns that were unique to each base restorative material; the materials appeared lighter than the underlying dentine (Fig. 2). Very few studies with root filled teeth have used the SEM to examine the fracture interfaces and analyse the mode of failure, and of those that did, only representative samples were assessed.[46,47] In the present study, the classifications for failure modes (Tables 2 and 3) were modified from previous criteria[46,48] to reflect a more accurate and detailed evaluation of the fractured surfaces possible with SEM.

***Failure mode of* resin composite**

Most teeth showed a predominance of adhesive failure and minor cohesive failure of the resin composite at the restoration-tooth interface, irrespective of the base material, which may be due to the high cohesive strengths of the resin composite and enamel compared with resin composite's bond strength to enamel.

Failure mode of GIC

The fractured dentine surfaces of almost all the GIC specimens showed mainly cohesive failure of the cement with only minor areas of adhesive failure as apparent from the presence of exposed dentinal tubules (Fig. 2A). Visible bur marks in the cavities indicated that the areas of GIC cohesive failure were very thin and even possibly within the ionic exchange or hybrid layer. Examination of the GIC on the corresponding fractured surfaces showed areas of cohesive failure that were similar in appearance with those found in other GIC fracture studies.[49,50]

Conventional GIC displays brittle fracture behaviour,[51] while ZPC, RM-GIC and resin composite undergo permanent deformation before fracturing, indicating that these materials did not undergo brittle fracture.[52]

Failure mode of ZPC

In the ZPC group, the areas of cohesive failure were mostly concentrated at the periphery of the base restoration, where the Durelon™ had possibly bonded to the enamel (Fig. 2D). The bond strength of Durelon™ to enamel is higher than to dentine[53] and thus may account for the cohesive failure at these areas if the bond strength exceeded the mechanical strength of the Durelon™ itself. Under high SEM magnification, the corresponding Durelon-fractured surfaces often showed tubular patterns indicating Durelon™ cement tags that were separated from the tubules on the fractured dentine surfaces.

Failure mode of Biodentine®

For the Biodentine group, areas of cohesive failure were characterised by circular areas of Biodentine® scattered over an amorphous dentine surface indicative of a smear layer because the cut dentine surfaces were not conditioned (Fig. 2B). These areas may indicate failure at the 'mineral infiltration zone' that forms between tricalcium silicate cement and dentine, or areas where voids and bubbles within the cement were present.

Other studies have reported similar findings where most Biodentine specimens failed adhesively with few showing cohesive or mixed failure within the Biodentine®.[48] In contrast, one study reported that the majority of Biodentine specimens failed cohesively.[54] These differences in findings could be attributed to different storage and loading conditions, including the number of storage days before testing. One recent study showed that Biodentine® is a weak material in its early setting phase and recommended delaying the placement of resin composite for more than two weeks, when using Biodentine® as a base material under resin composite, to allow intrinsic maturation to withstand the contraction forces of the resin composite.[55]

Failure mode of DCRC

The predominantly adhesive failure of the LuxaCore® agreed with other SEM studies.[56,57] Exposed dentinal tubules were often clearly visible on the fractured dentine surfaces, with the corresponding detached resin tags found on the LuxaCore® surface on the opposing fracture fragments (Figs. 2E & F). This pattern may be due to the resin core resisting deformation and fracturing at higher loads.[58] Variations and imperfections may act as crack-initiation points within the bonding interface and contribute to adhesive failure.[59] Areas of cohesive failure of the LuxaCore® typically had minimum voids, in contrast with the GIC and ZPC groups that had numerous voids (Figs. 2A & D) as previously reported.[60]

Conclusion

Several traditional and contemporary restorative materials can be considered as appropriate intermediate bases under direct resin composite restorations in root filled teeth. This laminate restorative technique appears to provide fracture strengths that can withstand normal and maximum masticatory function. The choice of base material may have an influence on the failure mode, which may have implications on the clinical presentation of fractures of root filled teeth but further research in this area is required.

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Table 1: Restorative materials used.

Composition	Manufacturer
Bis-GMA, UDMA, Bis-EMA, silica/zirconia particles (60%)	3M ESPE, St Paul, USA
Liquid: distilled water (50%), polyacrylic acid (40%) Powder: alumino silicate glass (95%), polyacrylic acid powder (5%)	GC Corporation, Tokyo, Japan
Liquid: water (50-65%), polyacrylic acid (30-50%) Powder: zinc oxide (85-95%), tin difluoride (1-10%), tin dioxide (1-5%)	3M ESPE, St Paul, USA
Bis-GMA, UDMA, benzoyl peroxide, CQ, barium glass (69%), pyrogenic	DMG, Hamburg,
Liquid: water, calcium chloride, polycarboxylate Powder: tricalcium silicate (80.1%), dicalcium silicate, calcium carbonate	Septodont, Saint Maur Des Fossés,
Water (70-80%), polyacrylic acid (20-30%)	3M ESPE, Seefeld,
Primer: 2-hydroxyethyl methacrylate (10-30%), 10-methacryloyloxydecyl dihydrogen phosphate, hydrophilic aliphatic dimethacrylate, dl-CQ,	Kuraray, Osaka, Japan
Pre-Bond: ethanol arylsulfinate solution (95-100%) Bond A: Bis-GMA, monomethacrylate, catalyst Bond B: Bis-GMA, monomethacrylate , dimethacrylate, carboxylic	DMG, Hamburg, Germany

Bis-GMA, Bisphenol A diglycidyl ether dimethacrylate; UDMA, urethane dimethacrylate; Bis-

Product	Description
Filtek™ Z250 (RC)	Light-cured resin composite
GC Fuji IX™ GP	Conventional glass ionomer
Durelon™ (ZPC)	Zinc polycarboxylate
LuxaCore®	Dual-cure resin
Biodentine®	Tricalcium silicate cement
Ketac™	Dentine
Clearfil™ SE Bond	Adhesive bonding system
LuxaBond® Total Etch	Etch-and-rinse adhesive system

Table 2. Modes of failure for resin composite (RC).

Failure Mode	Classification	Description
1	Adhesive failure	Adhesive failure only.
2	Mixed failure (A)	Predominantly adhesive failure with minor cohesive failure. If the RC appeared to be visible on more than 50% of the enamel surface then it was classified as predominantly adhesive failure.
3	Mixed failure (B)	Relatively equal amounts of adhesive and cohesive failure of the RC.

Table 3. Modes of failure for base material.

Failure mode	Classification	Description
1	Adhesive failure	Adhesive failure only.
2	Mixed failure (A)	Predominantly adhesive failure with minor cohesive failure. If the base material appeared to be visible on more than 50% of the dentine surface then it was classified as

		predominantly adhesive failure.
3	Mixed failure (B)	Predominantly adhesive failure with minor cohesive failure, and minor cohesive failure of dentine.
4	Mixed failure (C)	Relatively equal amounts of adhesive and cohesive failure.
5	Mixed failure (D)	Predominantly cohesive failure with minor adhesive failure.

Table 4. Mean fracture loads (N) by treatment group.

Treatment	Mean Fracture Load (N)	95% CI
DCRC	424	(388, 461)
GIC	415	(378, 452)
Biodentine®	399	(362, 436)
ZPC	371	(334, 408)
Control	207	(170, 244)

CI, confidence interval

Table 5 Distribution of fracture level and interface by treatment group.

Treatment Group	Level of Fracture			Fracture Interface	
	Above CEJ	At CEJ	Below CEJ	Buccal	Lingual
GIC	2	8	10	17	3
ZPC	4	7	9	18	2
Biodentine®	0	12	8	19	1

DCRC	1	7	12	12	8
Control	1	5	14	20	0
Total	8	39	53	86	14

CEJ, cemento-enamel junction

Table 6 Distribution of failure modes of the resin composite (RC) and base material by treatment group.

Treatment Group	RC Failure Mode (see Table 2)			Base Failure Mode (see Table 3)					Total
	1	2	3	1	2	3	4	5	
GIC	3	12	5	0	0	0	1	19	20
ZPC	2	14	4	0	20	0	0	0	20
Biodentine®	3	15	2	0	10	2	8	0	20
DCRC	2	12	6	0	10	5	5	0	20
Total	10	53	17	0	40	7	14	19	80

Figure legends

Figure 1: A mounted and restored specimen prior to loading.

Figure 2: SEM images (magnification x1000) of the failure modes of the four base materials.

(A) Typical appearance of a fractured dentine surface of teeth restored with GIC, which is mostly covered with a thin layer of cement with minor areas of exposed dentinal tubules (*black arrowheads*), indicating a predominantly cohesive failure with minor adhesive failure of the GIC. *(B)* Typical appearance of a fractured dentine surface of teeth restored with Biodentine®, showing characteristic circular areas of the cement (*black arrows*) scattered over an amorphous dentine surface. *(C)* A typical fractured surface of teeth restored with Durelon™ showing an abundance of dentinal tubules, with minor scattering of the Durelon™ cement (*white arrow*). This indicates a predominantly adhesive failure with minor cohesive failure of the cement. *(D)* Areas of cohesive failure of Durelon™ *(ZPC)* are typically concentrated at the periphery, which shows an abundance of air bubbles that is characteristic of cements formed by mixing a liquid with a powder component. The fracture lines in the Durelon™ (*white arrowheads*) are likely artefacts created during drying of the specimen when it was placed in vacuum within the SEM unit. Adjacent to this are exposed dentinal tubules where adhesive failure occurred *(DT)*. *(E)* Fractured dentine surface of a tooth restored with LuxaCore® showing minor scattered areas of the resin core (*black arrowheads*). The presence of exposed dentinal tubules (*white arrows*) indicates predominantly adhesive failure. *(F)* The corresponding fracture fragment of the same tooth in *(E)*, showing the abudance of resin tags on the LuxaCore® that separated adhesively from the dentine.

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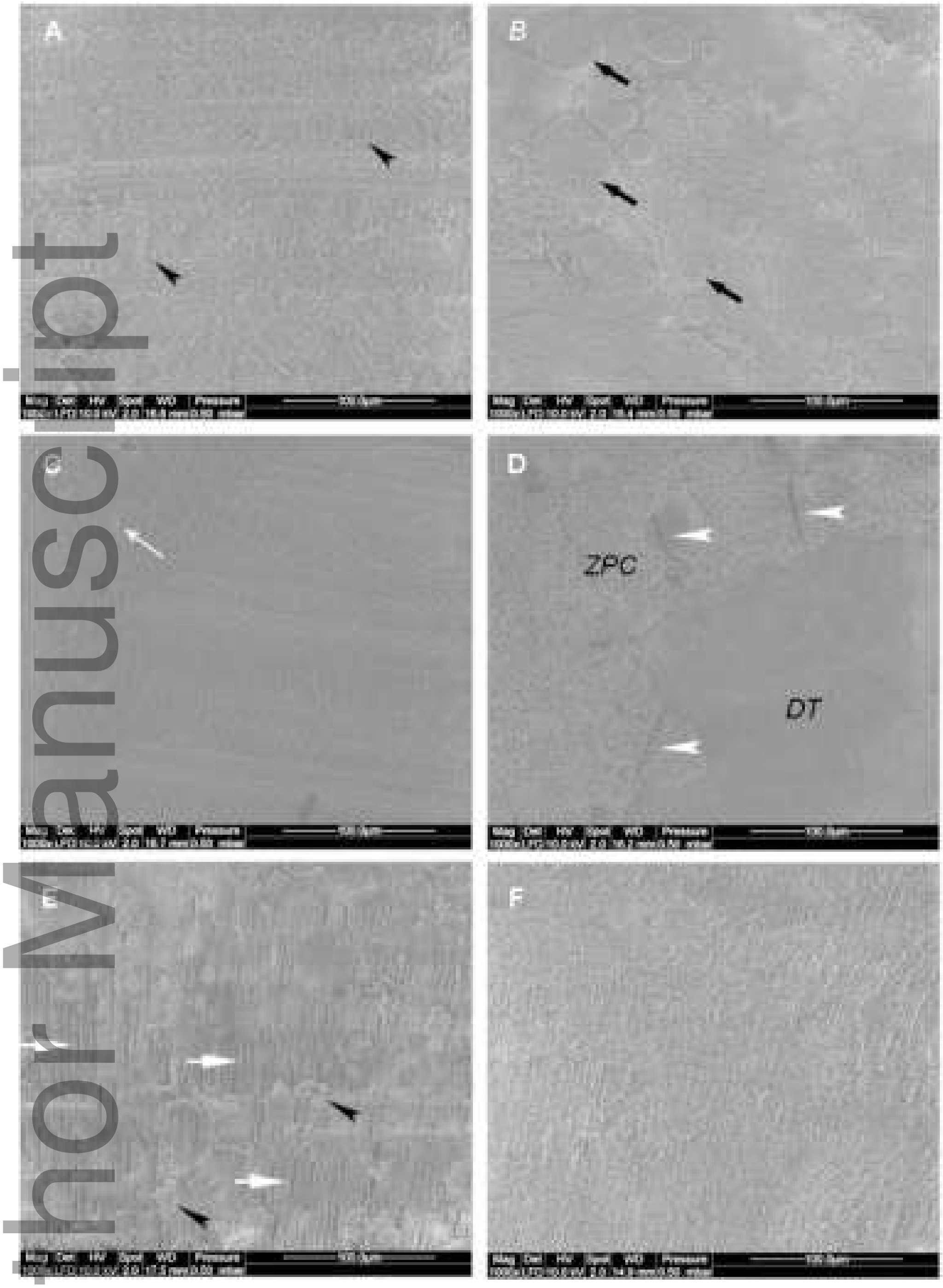

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