JOURNAL OF MATERIALS SCIENCE: MATERIALS IN MEDICINE **9** (1998) 517–521

Comparison of the wet and dry fatigue properties of all ceramic crowns

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The purpose of this paper was to investigate the influence of fatigue on the fracture strength of In ceram, optimal pressable ceramic (OPC™) and IPS Empress in both wet and dry environments. Twenty-six crown shapes 8 mm in diameter and 8.5 mm in height were fabricated for each ceramic system. For each ceramic system, ten specimens were tested for fracture strength without fatiguing. The second group was submitted to a fatigue and fracture test in a dry (eight specimens) and a third group in a wet (eight specimens) environment using an Instron testing machine. The results were statistically analysed using a Mann–Whitney test. The results indicated that: (i) the fracture strength for In ceram was significantly stronger than OPC™ and IPS Empress ($p < 0.05$) – no difference was found between OPC™ and IPS Empress; (ii) fatiguing and fracture testing showed a significant decrease in the fracture strength for In ceram and IPS Empress in the wet environment and no difference was found in the dry environment – no difference was found for OPC™; and (iii) when fatigued in a dry environment, In ceram crown shapes were significantly stronger than OPC™ and IPS Empress ($p < 0.05$) – the same statistical differences were found when fatigued in a wet environment.

1. Introduction

Nowadays aesthetics are considered important and metal-free ceramic restorations are the preferred choice. Aesthetics are improved when metal is eliminated and is replaced by translucent porcelain. Modern ceramics such as Optec-HSP [1], Dicor [2–5], In ceram [6–8] and IPS Empress [7, 9] have been introduced and recently optimal™ pressable ceramic (OPC™) has been introduced in which crowns are fabricated by a similar process as in IPS Empress. These ceramics have shown improved form, function, physical properties and satisfactory aesthetics.

However, some factors can cause intra-oral porcelain fracture, for example, microdefects within the materials, improper design, impact load and fatigue load [10, 11]. Fatigue is a mode of fracture whereby a structure eventually fails after being repeatedly subjected to loads that are so small that one application apparently does nothing detrimental to the component [12]. It is estimated that 90% of all mechanical failures are caused by fatigue [13].

Ceramics are brittle materials that have limited tensile strength and are subject to time-dependent stress failure. These are attributable to the presence of microdefects within the material and degradation in an aqueous environment resulting from subcritical crack growth stress corrosion [14]. Some studies have shown that there is a decrease in strength when porcelain is tested in water as compared to testing dry [15, 16].

The purpose of this paper was to study the influence of fatiguing on the fracture strength of three ceramics systems (OPC™, In ceram and IPS Empress) in wet and dry environments luting with a glass ionomer.

2. Experimental procedure

A master die with approximately the same dimensions as a premolar was made from brass (Fig. 1).

Wax patterns of OPC™ (Jeneric Pentron) and IPS Empress (Ivoclar Vivadent) crowns were made using a split brass mould of a previously waxed crown

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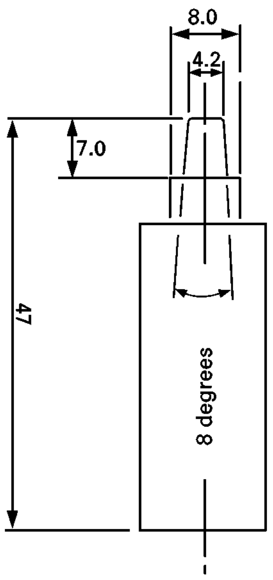

Figure 1 Schematic drawing of the brass master die, (all corners were radiused to 0.5 mm).

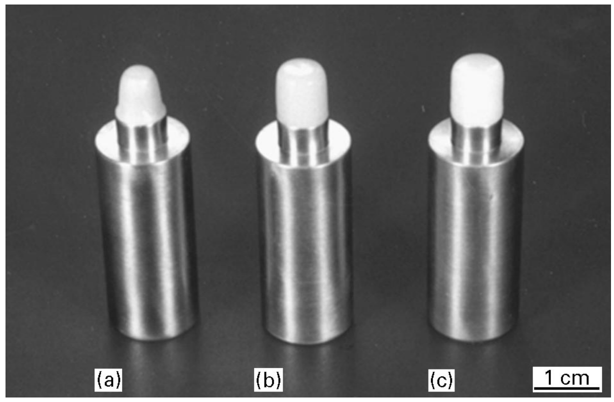

Figure 2 Samples of In Ceram core (a), In ceram complete crown shape (b), and OPC™ crown shape (c).

shape. The brass die was coated with two layers of die spacer, and molten wax was then applied to the brass die, which had been placed in a split brass mould as used in previous work [17] to produce a complete crown shape 8.00 mm in diameter by 8.5 mm in height. The wax patterns were sprued and attached to a muffle base with a surrounding paper cylinder.

OPC™ wax patterns were invested using 200 g OPC™ special investment (Jeneric Pentron) mixed with 38 ml OPC™ investment liquid and 4 ml distilled water for 60 s. The wax was eliminated in a furnace (5635, Kavo, EWL) by heating at 3 °C min^{-1} to 950° for 90 min. Twenty-six samples were pressed using OPC™ in an automatic press furnace (Jeneric Pentron) using the manufacturer's instructions and 5 bar pressure. The OPC™ ingots were not preheated in the burnout furnace before the pressing procedure. After cooling the samples were devested using glass beads (50 μm) at 2 bar pressure. Sprues were removed with a diamond disc (006, Bracon) and ground with a diamond burr. Specimens were fired in a porcelain furnace (Multimat MC II, Dentsply) using two stain firings and one glaze firing, using the recommended glaze material and manufacturer's firing cycles (Fig. 2).

IPS Empress wax patterns were invested using 200 g of IPS Empress investment mixed with 30 ml of IPS Empress investment liquid and 12 mls of distilled water for 60 seconds. Waxs was eliminated in a burn-out furnace, by heating at 3 °C/min to 850 °C and holding for 90 min. The heat-pressed ceramic crown shapes were pressed in an automatic press furnace following the manufacturers instructions and 5 bar pressure. Samples were fired using three stain firings and two glaze firings, using the recommended glaze material and firing schedule. A total of 26 crown shapes were fabricated for IPS Empress.

In ceram crown shapes were produced by coating a brass die with three layers of die spacer (Vita) and impressions were made using an addition cured silicone material (Express, 3M Dental Products) with a metal ring. These impressions were poured with In ceram special plaster using a liquid : power (l : p) ratio of 0.23 ml g^{-1} to make refractory models. In ceram powder slip was prepared according to the manufacturer's instructions and was applied to the models. A sculpturing device similar to that used by Philp and Brukl [18] was utilized to ensure a uniform thickness of core (0.5 mm). After applying a stabilizer, the coping was fired on the plaster dies then glass infiltrated in a second firing. Excess glass was removed and the veneer porcelain (Vita Alpha, Dentine porcelain) was then applied to the core, which had been placed in a split brass mould [17] to make a complete crown shape 8.0 mm in diameter and 8.5 mm in height (Fig. 2). A total of 26 crown shapes were fabricated for In ceram systems.

After glazing, the crown shapes were cemented onto the brass die with glass ionomer cement (RGI-lutrex). The cement was mixed according to the manufacturer's instructions. The crown shapes were filled with cement with firm pressure and excess cement was removed and immediately placed under a 2.7 kg static load for 10 min. The samples were stored in distilled water at room temperature for 24 h before testing.

The crown shapes were divided into two groups. One group was tested for compressive strength without fatiguing, in an Instron universal testing machine. A preload of 20 N was applied to the centre of the occlusal surface of the crown shape with a 4 mm diameter stainless steel ball and then, at a crosshead speed of 1.0 mm min^{-1}, it was loaded until fracture occurred. A total of ten crown shapes were submitted to this compressive strength test for each ceramic system (the fracture strength data of the crown shapes were submitted to a Mann–Whitney statistical analysis). The second group was submitted to a fatigue regime of 10 000 cycles prior to fracture testing, cycling between a minimum and maximum load of 20 and 300 N, applied with a force profile in the form of a sine wave at 1 Hz. After, the specimens were tested to failure as described above. The tests were carried out in either a dry or a wet environment. A total of eight crown shapes were tested in each environment for each porcelain system. The fracture surfaces of the crown shapes were gold coated and then examined using a scanning electron microscope (SEM, Cambridge S90B).

3. Results

The mean load at complete fracture and also after fatiguing and fracture testing in wet and dry environments is shown in Fig. 3 and Table I.

Fig. 3 shows that for In ceram crown shapes there were significant differences between fracture tested and wet fatigue and fracture tested groups ($p < 0.05$). No difference was found between fracture test and dry fatigue and fracture tested groups. In spite of dry fatigue and fracture tested crowns showing higher values compared with wet fatigue and fracture tested groups, the results were not at a statistically significant level. The same results were found for IPS Empress. For OPC™ no statistical difference was found between fracture tested and fatigue and fracture tested groups in the wet and dry environments.

Table I shows that the mean fracture strength for In ceram crown shapes was 1256 N (ranging from 1171 to 1457 N), for OPC™ it was 997 N (ranging from 708 to 1371 N), and for IPS Empress it was 817 N (ranging from 714.1 to 1054 N). The fracture strength for In ceram crown shapes was significantly higher than for OPC™ and IPS Empress ($p < 0.05$). No statistical difference was found when OPC™ was compared with IPS Empress.

Following fatiguing and fracture testing, the mean fracture strength for In ceram dry fatigued and fracture tested was 1156 N (ranging from 990 to 1264 N), and wet fatigue and fracture tested it was 1075 N (ranging from 799.4 to 1280 N). For OPC™ dry fatigued and fracture tested, the mean was 924 N (ranging from 686.4 to 1145 N) and wet it was 843 N (ranging from 561.3 to 1001 N). For IPS Empress fatigued in a dry environment, the mean fracture strength was 756 N (ranging from 507.2 to 1054 N) and fatigued wet and fracture tested it was 663 N (ranging from 530 to 829.2 N). In ceram crown shapes dry fatigued and fracture tested were significantly stronger than OPC™ and IPS Empress ($p < 0.05$). No difference was found between OPC™ and IPS Empress. The same results were found when crown shapes were fatigued in a wet environment and fractured (Table I).

Fig. 4 shows a SEM image of the fatigue surface of an OPC™ crown shape. In all cases, the cement remained adherent to the OPC™ and the figure shows the failure of the cement at the cement–porcelain interface. This is thought to be due to initial fatiguing, prior to mechanical testing.

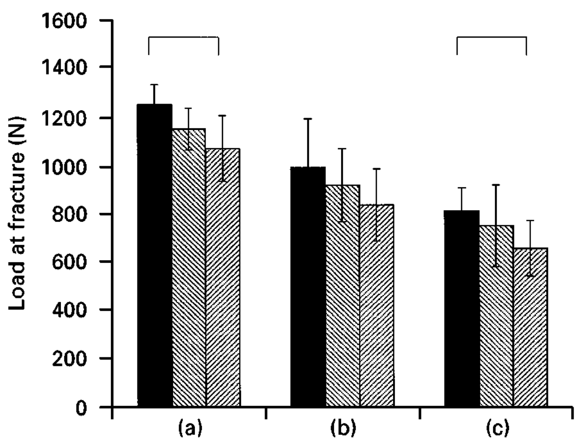

Figure 3 Means of fracture tested (■) and fatigue and fracture tested specimens, fatigued in dry (▧) or wet (▨) environments, for (a) In ceram, (b) OPC™, and (c) IPS Empress crown shapes luted with glass ionomer cement (lines indicate statistically significant difference; Mann–Whitney, $p < 0.05$).

4. Discussion

Several factors can contribute to the variation in fracture strength of a clinical ceramic crown for example, the shape of the prepared tooth, the luting agent, crown thickness, direction of the applied load and location of the applied load [3, 14, 19].

In this study, a split brass mould was utilized to produce a wax crown shape with the same dimensions for OPC™ and IPS Empress. A sculpturing device similar to that used by Philp and Brukl [18] was utilized to give a uniform In ceram core thickness and a split brass mould was utilized to give the complete crown shape with Vita Alpha dentine porcelain. Twenty brass master dies with the same dimensions were utilized. It is important to make specimens with the same thickness because small variations can affect the strength of the restoration [20]. All specimens

TABLE I The mean load (N) at complete fracture (standard deviation values shown in brackets) and after fatiguing in either wet or dry environments; all luted with glass ionomer cement[a]

Material	Fracture test only	Fatigue and fracture tested[a]	
		Dry	Wet
In ceram	1256 (84)a	1156 (87)a	1075 (136)a
OPC™	997 (200)b	924 (151)b	843 (149)b
IPS Empress	817 (96)b	756 (169)b	663 (114)b

[a] Means followed by the same letter in the column, indicate no statistical difference in Mann–Whitney test ($p < 0.05$).

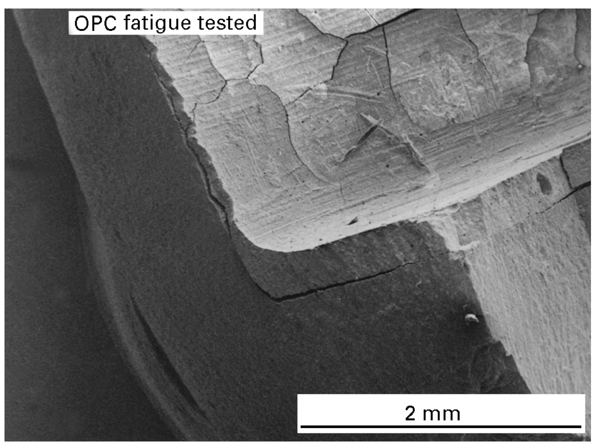

Figure 4 SEM image of fracture surface of a fatigued OPC™ crown shape.

were luted with glass ionomer (RGI-Lutrex) in accordance with the manufacturer's recommendation.

The point of force application to the fracture and fatigue test was the centre of the occlusal surface of the crown shapes. The biting force for posterior teeth can vary between 245 [21] and 540 N [22]. In our study fatiguing was carried out between 20 and 300 N.

Another variable that can contribute to failure of a ceramic restoration is the environment. In this study a decrease in strength was observed when In ceram, OPC™ and IPS Empress were tested in wet rather than a dry environment, but no statistical differences were found. De Long *et al.* [23] showed that statistically significant differences were not found among the control, fatigue only and corrosion-fatigue groups in artificial saliva. Sherril and O'Brien [15] and Fairhurst *et al.* [24] demonstrated that there is a decrease in fracture strength when porcelain is tested in water as compared to testing in a dry environment. Myers *et al.* [16] showed that ceramics demonstrated a susceptibility to stress corrosion fatigue when tested in water and Southan and Jorgensen [25] showed that the ability of a dental porcelain to sustain a static load in water decreased as duration of load application increased.

There are a number of factors that can affect a ceramic during fatigue testing, dependent on whether they were fatigued wet or dry. For the materials studied in this work, a major factor may be the presence of stress corrosion cracking, which may be accelerated in alumina or high alumina systems. Also, due to the nature of the specimens tested, moisture diffusion may be a factor. It is likely that the most significant source of moisture ingress is via the cement. However, in the tests carried out, the entrance route only offers a small area for ingress. However, moisture ingress may be accelerated by the presence of interfaces along which moisture migrates and the fatiguing may accelerate this.

It was observed also that for In ceram and IPS Empress crown shapes when submitted to the fracture test they were significantly stronger ($p < 0.05$) than when they were submitted to fatiguing followed by fracture testing in a wet environment. No difference was found in the dry environment. For OPC™ no statistical difference was found when the fracture test was compared with fatiguing followed by fracture testing in wet and dry environments. Yoshinari and Derand [14] compared the fracture and fatigue test, and showed that the strength of Vita Dur crowns decreased significantly after being subjected to preload cycling. The averages using zinc phosphate cement were: 1022 N fracture and 770 N with preload.

When the mean fracture strengths were compared, In ceram crown shapes (1256 N) were significantly stronger than OPC™ (997 N) and IPS Empress (817 N) ($p < 0.05$). No statistical difference was found between OPC™ and IPS Empress. Correr Sobrinho *et al.* [26] found that In ceram crown shapes (1901 N) were significantly stronger than IPS Empress (1583 N) luted with zinc phosphate. Probster [7] showed that anterior In ceram crowns have a higher fracture strength (964 N) than IPS Empress (814 and 750 N) luted with zinc phosphate. Grey *et al.* [8] testing a premolar with perpendicular loading, obtained 1609 N for In ceram with a 0.7 mm core and 1557 N for the metal ceramic. Correr Sobrinho *et al.* [17] found that In ceram crown shapes (2183 N) showed significantly higher fracture strengths than OPC™ (1814.5 N) and IPS Empress (1609 N) ($p < 0.05$) luted with glass ionomer (Fuji).

In this study when fatigue and fracture tested specimens were compared when tested in a dry environment, In ceram (1156 N) crowns were significantly stronger than OPC™ (924 N) and IPS Empress (756 N) ($p < 0.05$) crowns. No difference was found between OPC™ and IPS Empress. The same results were found in the wet environment. Yoshinari and Derand [14] utilizing inclined load after cyclic prestressing in water with a premolar got values statistically higher with premolar In ceram crowns (1060 N) than IPS Empress (891 N), Dicor (840 N) and Vitadur (770 N) crowns luted with zinc phosphate. Correr Sobrinho *et al.* [26] luted specimens with zinc phosphate, and showed that In ceram (1601 N) and OPC™ (1586 N) crowns were significantly stronger than IPS Empress (1374 N) crowns ($p < 0.05$) in a dry environment.

The larger difference found in this study when compared with results in previous work by Correr Sobrinho *et al.* [26] is probably because of the kind of cement that was used for fixing the specimens. Correr Sobrinho *et al.* [26] in another study used zinc phosphate and in this paper glass ionomer was used. It is probable that the glass ionomer cement could have deteriorated, resulting in a change of the crown shape support. Dental luting agents have poor wetting properties and, as the cements set, they contract and pull away from the restoration and the tooth [27]. This inability to fill the space between a crown and the tooth completely compounds the problem of stress transfer. It may be that a thin cement layer, characteristic of better-adapted crowns, is more relevant to the practical strength of a porcelain crown than the relative strength of the materials themselves [28].

Fatigue failure is initiated by microscopic cracks that develop in areas of stress concentration [29]. Kelly *et al.* [30] and Anusavice and Hojjatie [31] observed that the majority of the crown failures were initiated at the internal surface, showing this surface was placed under the greatest tensile stress or probably the location of the largest flaws and/or voids. Water uptake of the glass ionomer cement and subsequent transfer of tensile stresses to the crown interface could also be a relevant factor.

In ceram crown shapes demonstrated good mechanical properties probably because they had a core composition of approximately 85 vol % Al_2O_3 crystals [14] and voids and remaining flaws were almost completely filled with molten glass, providing a homogeneous, bubble-free core consisting of fine particles in a vitreous matrix [32]. The fracture resistance of OPC™ compared with IPS Empress is higher, probably due to OPC™ containing higher levels of leucite (approximately 55 vol %, [33]) compared with IPS Empress (24 vol %, [34]).

Although the use of a brass die does not reproduce natural teeth, because of the mismatch in mechanical properties compared to teeth, the die did provide a reproducible support. Furthermore, the results could have been affected by the use of glass ionomer cement for IPS Empress and OPC™. The manufacturers' recommend the use of specialist resin cements for OPC™ and IPS Empress. Some studies have shown apparent fracture strength increase of ceramics crowns bonded to resin cements [35–37]. Further research, however, aims at using natural tooth as a base and resin cement luting agent.

5. Conclusions

1. The fracture resistance for In ceram (1256 N) crown shapes was significantly stronger than OPC™ (997 N) and IPS Empress (817 N) ($p < 0.05$) . No statistical difference was found when OPC™ was compared with IPS Empress.

2. The fracture strength of In ceram crown shapes decreased significantly after wet fatiguing compared with non-fatigued samples, but did not differ from dry fatigued samples. The mean values were: In ceram fracture tested only, 1256 N; dry and wet fatigued, 1156 and 1075 N, respectively. In spite of dry fatigued specimens showing higher fracture strengths compared with wet fatigued there was no statistically significant difference found. The same statistical results were found for IPS Empress. No statistical difference was found when the non-fatigued fracture strength of OPC™ was compared with wet and dry fatigued fracture strengths.

3. Following dry fatiguing, the mean fracture strength for In ceram (1156 N) was significantly higher statistically, compared with OPC™ (924 N) and IPS Empress (756 N) ($p < 0.05$) . No difference was found between OPC™ and IPS Empress. The same results were found for fatiguing in a wet environment.

Acknowledgements

The authors would like to thank FAPESP (Fundacao de Amparo a Pesquisa do Estado de Sao Paulo) process 1996/4208-8 for financial support for this project. We also express our thanks to Dr Carl Panzera of American Thermocraft and Ivoclar Vivadent for providing the ceramic and cement materials.

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Received 3 September 1997
and accepted 26 January 1998