The effect of preparation taper on the resistance to fracture of monolithic zirconia crowns

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ABSTRACT

Objective. Monolithic zirconia crowns have become a viable alternative to conventional layered restorations. The aim of this study was to evaluate whether the taper, and thus wall thickness, of the abutment or pre-defined cement space affect the fracture resistance or fracture mode of monolithic zirconia crowns.

Methods. A model tooth was prepared with a taper of 15° and a shallow circumferential chamfer preparation (0.5 mm). Two additional models were made based on the master model with a taper of 10° and 30° using computer-aided design software. Twenty monolithic 3rd generation translucent zirconia crowns were produced for each model with pre-defined cement space set to either 30 μm or 60 μm (n = 60). The estimated cement thickness was assessed by the replica method. The cemented crowns were loaded centrally in the occlusal fossa at 0.5 mm/min until fracture. Fractographic analyses were performed on all fractured crowns.

Results. The load at fracture was statistically significant different between the groups (p < 0.05). The crowns with 30° taper fractured at lower loads than those with 10° and 15° taper, regardless of the cement space (p < 0.05). The fracture origin for 47/60 crowns (78%) was in the cervical area, close to the top of the curvature in the mesial or distal crown margin. The remaining fractures started at the internal surface of the occlusal area and propagated cervically.

Significance. The fracture resistance of the monolithic zirconia crowns was lower for crowns with very large taper compared to 10 and 15° taper even though the crown walls were thicker.

1. Introduction

Material choice, preparation and cementation technique affect the clinical performance of all-ceramic dental crowns in terms of fracture rates, retention, function and/or aesthetic [1–3]. The use of yttria-stabilized zirconia (Y-TZP) is increasing due to its high flexural strength, fracture toughness and good biocompatibility [4–6]. Higher sintering temperature and longer dwell-time result in larger grain size [7–9]. Higher
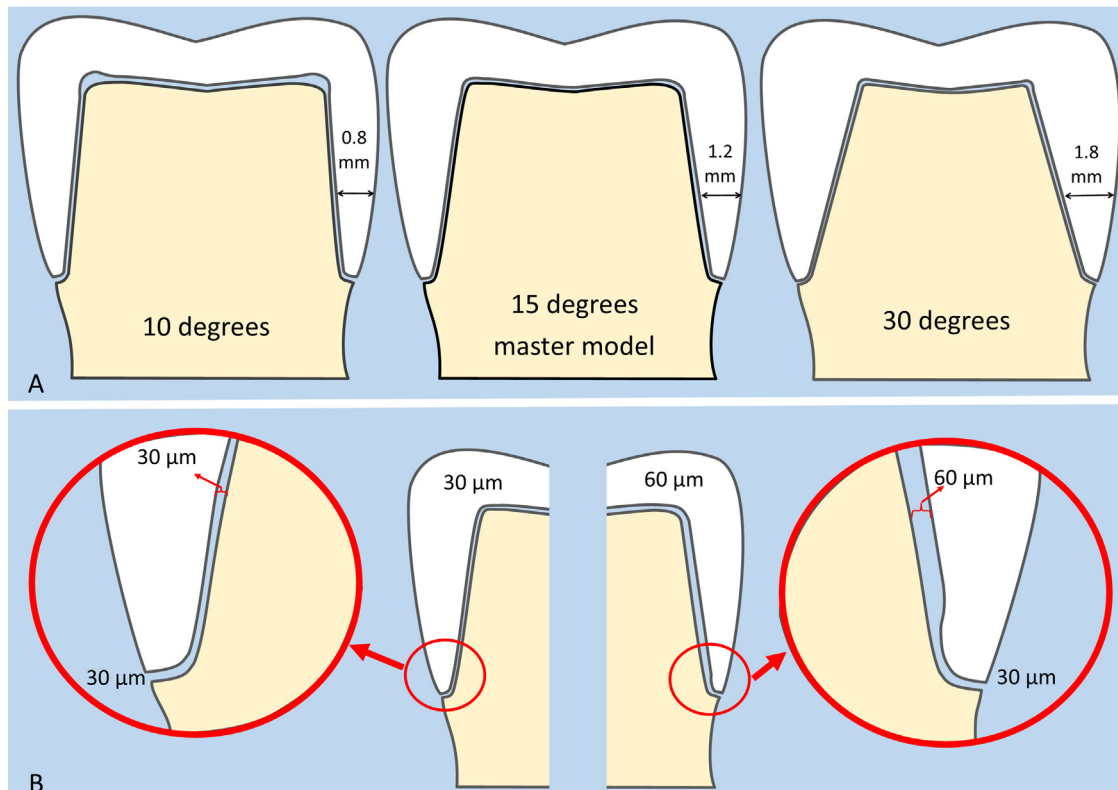
Fig. 1 – Overview of the study groups. A: The three different models with taper of 10°, 15° and 30°. B: Twenty crowns were produced of each model; ten with a cement space of 30 μm (left) and ten with 60 μm (right). The outer limit of the crowns remained unchanged for all groups.

amount of yttria results in a higher proportion of cubic phase crystals [6,10]. These alteration of the material composition and production method has resulted in more translucent zirconia materials (often referred to as 3rd generation zirconia), which are aesthetically acceptable even without a veneering layer, "monolithic zirconia crowns" [6]. But the alterations that increase the translucency cause a reduction in the flexural strength and fracture toughness [9].

Fractures and loss of retention are the main reasons for complications with zirconia crowns [11]. The introduction of monolithic zirconia crowns has reduced the problems with chipping and delamination [12,13]. From a biological perspective the ideal situation is to remove as little tooth substance as possible. This usually conflicts with required material thickness to achieve acceptable aesthetics and flexural strength [14]. Elimination of a veneering layer reduces the need for preparation depth. Material thickness occlusally of 3Y-TZP of 0.5 and 1.0 mm still gives higher loads at fracture than a 1.5 mm thickness of lithium disilicate reinforced glass ceramic [9,15]; a thickness of 1 mm has similar strength to that of traditional metal-ceramic crowns [13]. The few studies regarding thickness of monolithic zirconia crowns have focused solely on occlusal thickness [13,16]. Several studies indicate all ceramic crowns mainly fail from fracture initiated in the crown margins [17]. It is thus probable that margin- or wall thickness is of greater importance for fracture resistance than occlusal thickness.

As the crown contour is primarily driven by anatomic structures, aesthetics and hygienic design, the cement space and the tooth abutment preparation are the variables that can be adjusted while maintaining the crown's material thickness. The cement space is pre-defined by the operator and dental technician when manufacturing the crown. The internal and marginal fit is the actual fit when placing the crown. There is no consensus about the clinically acceptable internal or marginal fit of the crown, but most publications recommend a marginal fit below 120 μm [18,19]. Poor marginal fit has clinical implications for adhesion of oral bacteria that can lead to secondary caries and gingival inflammation and subsequent deterioration of periodontal health [20–24]. Too narrow axial cement space prevents cement flow at the crown margin, and thus result in too thick of occlusal cement layer and axial discrepancy of the crown at the cervical margin.

Preparation techniques for dental crowns have varied greatly over time [25,26], ranging from preparations with small taper (convergence angle) and sharp edges, depending on mechanical retention, to rounded edges and large taper depending on adhesive cement. Design of the restoration, size and distribution of material flaws, residual stress, degradation, ceramic-cement interfacial features, wall thickness, elastic moduli of the material and forces applied are all contributing factors to crack initiation and propagation [27,28]. There is still limited understanding of how specific design variables contribute to fracture resistance of monolithic zirco-

Code	Brand name	Production method	Material composition	Grain size
DDX2	Dental Direkt DD CubeX[2]	Soft-machined	ZrO_2 + $HfO_2 \geq 90\%$, $Y_2O_3 < 10\%$, $Al_2O_3 < 0{,}1$ %, other oxides $\leq 0.005\%$.	0,36 μm

Table 1 – The material used with brand name, production method, material composition and grain size. The data are from the manufacturer.

nia crowns. Both cement thickness and taper of the abutment affect the mechanical retention, seating and marginal fit, but it is uncertain whether it also affects the fracture resistance [25]. The consequences of a larger taper will inevitably be increased wall thickness given the same anatomical form of the outer contour. Therefore, the aim of this study was to evaluate whether pre-defined cement space or taper, and thus wall thickness of the restoration, affect the fracture resistance of monolithic zirconia crowns.

2. Material and methods

A synthetic second premolar tooth (KaVo Dental GmbH, Biberach, Germany) of the lower jaw, #45, was prepared with a circumferential shallow chamfer of 0.5 mm, a taper of 15° and rounded edges. The depth and taper were measured repeatedly during preparation by light microscopy (Leica Model TM-505/510, Mitutoyo American Corporation, Illinois, USA). At 10× magnification with a designated software (Leica Application suite V4.4) until correct depth and 15° were obtained. An A-silicone impression (Affinis, 3M ESPE, Minneapolis, USA) was used to produce a stone model of the preparation and adjacent teeth (Tannlab A/S, Oslo, Norway). The model was digitally scanned to produce a 3D model (3Shape Dental Designer, Copenhagen, Denmark). The taper was controlled to be 15 (±2) degrees and two additional models with 10° and 30° taper were digitally designed based on the master model in the software. The finish line and the chamfer depth were identical in all groups.

The pre-defined cement space, hereby referred to as cement space, was digitally set to either 30 μm or 60 μm on all three models (Fig. 1). Ten identical monolithic zirconia crowns 5Y-TZP (DD CubeX[2], Dental Direkt GmbH, Spenge, Germany) were prepared for each of the six test groups as presented in Table 1, resulting in a total of 60 crowns. The procedures followed manufacturer's recommendations. Physical models of the three digital designs were produced by additive manufacturing (ProJet 3510 MP, 3D Systems, Rock Hill, USA). Twenty identical epoxy models were produced for each design (EpoFix, Struers A/S, Ballerup, Denmark). One epoxy model was made to fit each of the individual crowns.

All the crowns were inspected for cracks, margin chipping and other defects using a light stereomicroscope (Leica M205 C, Heerbrugg, Switzerland) equipped with a LED ring light at 10× magnification. Pictures were taken for documentation at 10× and 20× magnification if defects were detected. The quality of the crown margins was graded according to a 5-graded scale [17]. For the 20 crowns matching the master model, the estimated cement thickness was measured using a replica method measuring silicone film thickness for cement thickness as described in detail elsewhere [29].

The crowns were cemented to their respective epoxy model with standardized pressure (110N), using glass-ionomer cement (Fuji One, GC Corporation Tokyo, Japan). Excess cement was removed after setting, and the crowns placed in distilled water at 37 °C for 24 (±1) h. The crowns were subsequently loaded centrally at the occlusal surface with a horizontal steel cylinder with a diameter of 13 mm using a servo-hydraulic material testing system (MTS 852 MiniBionix II, Minnesota, USA) at 0.5 mm/min until fracture. The steel cylinder was cushioned with a 3 mm thick rubber disc of hardness 90 Shore A to distribute the load evenly and to avoid contact damage during loading. The specimens were maintained in water at room temperature during loading. The load at fracture was recorded. Each crown was inspected using the aforementioned stereomicroscope to assess the fracture mode and origin.

The statistical analysis was performed using a commercial software package (Stata 13.1. StataCorp LLC, College Station, USA). Results for the load at fracture were evaluated using a Kruskall–Wallis test, supplemented with Kruskall–Wallis equality-of-populations rank test to analyse the differences among the groups. A one-way ANOVA test was used to assess the internal fit. Spearman's rank correlation test was used to evaluate correlations between variables. The significance level was set to 0.05.

3. Results

3.1. Crown margin quality

There was no significant difference in the grade of margin defects between the groups ($p > 0.05$, Fig. 2). Furthermore, there was no significant correlation between the grade of defects and load at fracture within the groups ($p > 0.05$). The size and number of defects in the sample were, in general, small.

3.2. Cement thickness

The estimated cement thickness values of crowns with 15° taper and different settings for cement space measured by the replica method, are shown in Fig. 3. There was no significant difference in the occlusal cement thickness or the marginal cement thickness between the groups with different cement space ($p > 0.05$). The group with 60 μm cement space had significantly reduced cement thickness compared to the group with cement space of 30 μm ($p < 0.05$).

3.3. Load at fracture

There were significant differences in the load at fracture among the tested groups ($p < 0.05$) as shown in Fig. 4. Range for the different groups were 10° (1087N–2583N), 15° (642N–2495N) and 30° (771N–1769N). The specimens with a 30° taper had a significantly lower load at fracture than the other groups ($p < 0.05$). There were no significant differences in load at fracture between the groups with different cement space and identical taper ($p > 0.05$).
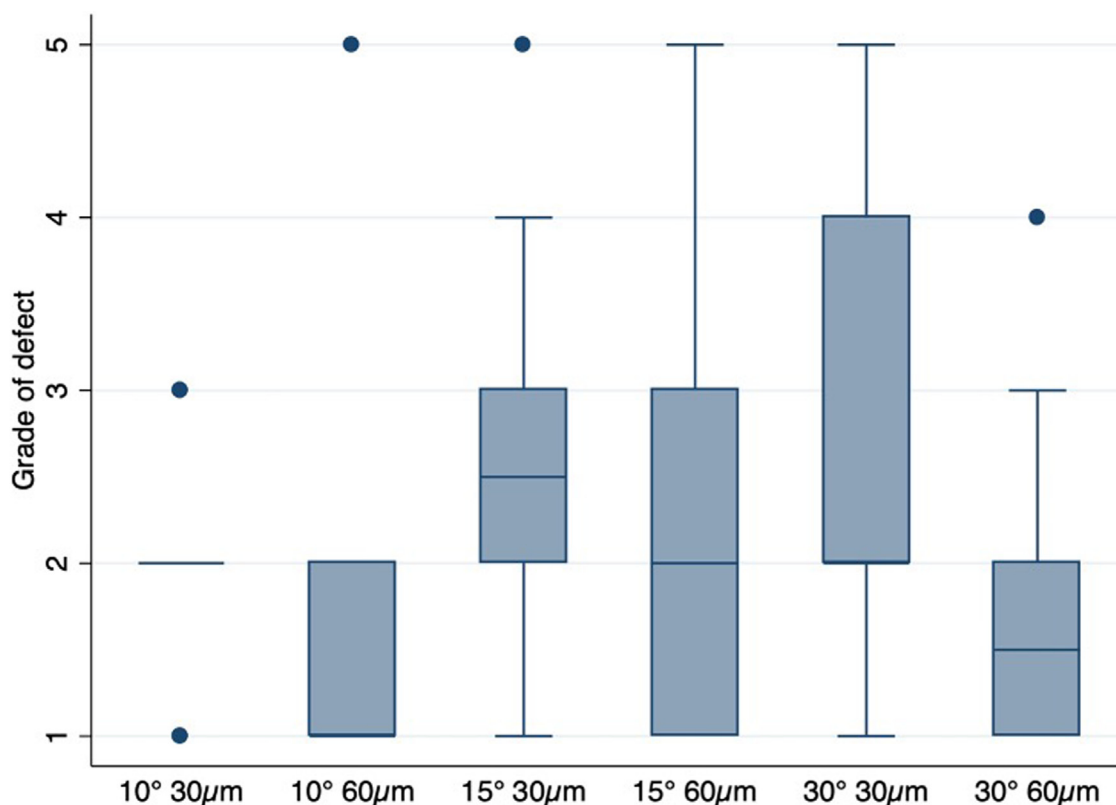
Fig. 2 – Tukey's boxplot illustrating the "grade of defect" of the groups. The bottom and top of the box represent the first and third quartiles, and the internal horizontal lines represent the median. The whiskers represent the maximum and minimum data within the 1.5 interquartile range (IQR). The dots represent outliers outside 3 IQR. There was no significant difference between the groups regarding the grade of defects (p > 0.05).

3.4. Fracture mode

Results from the fractographic analyses showed that the origin of fracture for 47 of the 60 crowns was in the cervical area. The fracture started close to the top of the curvature in the mesial or distal crown margin (Fig. 5). Thereafter, the crack propagated towards and through the occlusal area following the path of least resistance to the opposite cervical area. In the remaining thirteen of the crowns, the origin of fracture was in the occlusal area. Specifically, these fractures started at the internal surface and propagated to the external surface and to the approximal cervical area on both sides as shown in Fig. 6.

4. Discussion

Fracture resistance is a key requirement to the survival of all-ceramic crowns. The aim of this study was to identify whether taper of the abutment or pre-defined cement space affect the load at fracture, a clear metric of fracture resistance. The results indicated that the taper affected load at fracture, whereas pre-defined cement space did not. Furthermore, an increase of the taper to 30° decreased the load at fracture compared with a taper of 10° and 15° even though the crowns walls were much thicker.

Previous studies indicate that increased material thickness in crown walls, in general, increases the load at fracture [30–32]. To some extent, the present results contradict these studies as the crown walls were much thicker in the 30° taper group compared to the 10 and 15° groups. The margin thickness was, however, identical in all groups. There is a positive association between the elastic modulus of the material, wall thickness and the compressive strength. In addition, there is substantial evidence indicating that a thicker core material results in reduced risk of fractures [33–36]. These studies have, however, mostly focused on bi-layered structures and a direct comparison is difficult.

The importance of the crown geometry on the magnitude of marginal stress has been emphasized through results of previous finite element analyses (FEA) [33,37]. When a force is applied on top of the crown, most of the stress is distributed to the occlusal area and some stress is distributed through the axial walls of the crown [1]. The occlusal area of the preparation and wall thickness will vary as a function of the taper. Higher stress develops at the occlusal area when the taper of the preparation is small and, subsequently, when the occlusal area is increased [38]. A reduced occlusal area and, subsequently, a larger taper therefore results in larger stresses within the axial walls of the crown when compared to a smaller taper and larger occlusal area [39]. In addition, the height of the preparation influences the stress at the cervical areas [37]. One study indicates that smaller taper results
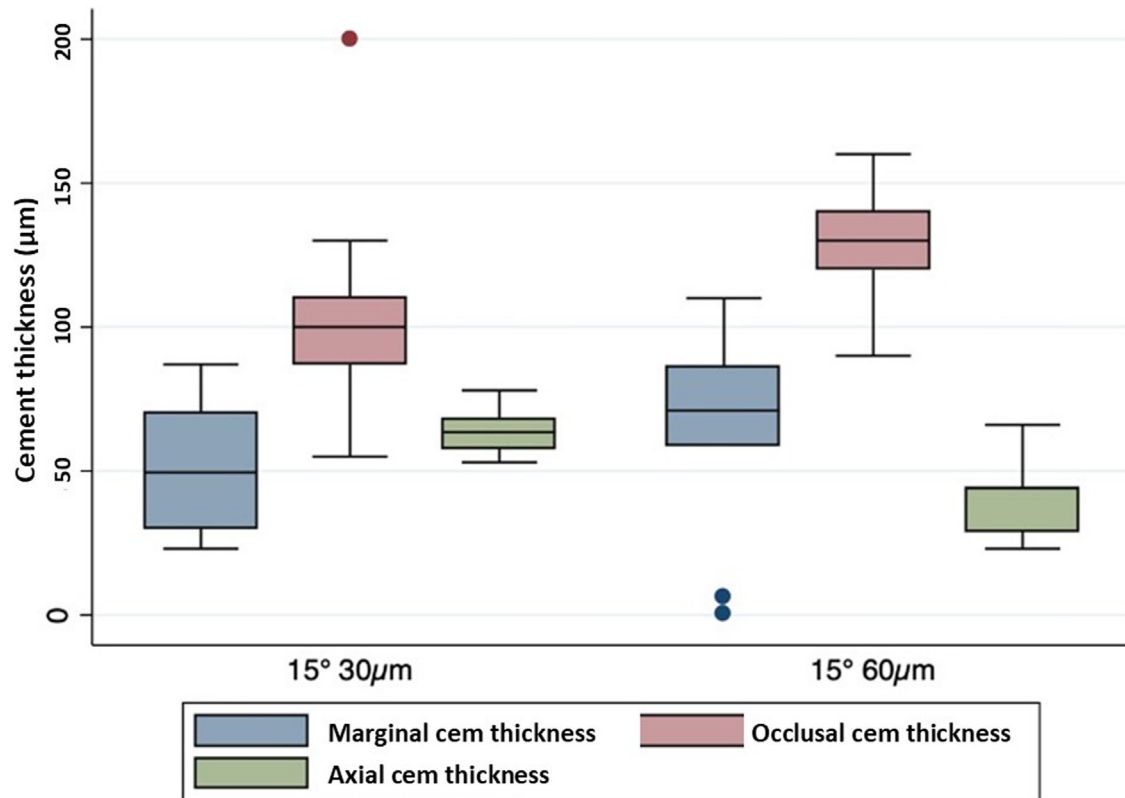
Fig. 3 – Tukey's boxplot of the cement thicknesses with the different pre-defined cement spaces. There was no significant difference of the occlusal and marginal cement thickness among the groups (p > 0.05). The group with cement space of 60 μm had significantly reduced axial cement thickness than the group with cement space of 30 μm (p < 0.05). See legend to Figure 2 for explanation of box-plot.

in lower stress [40], but another indicates the opposite [38]. Neither of these previous studies explain or explore the consequences of a reduction in stress at the occlusal area on crown fractures (location and mode). The fractographic analyses in the present study showed that most fracture origins were located cervically as evident in Fig. 5. Thus, understanding the stress in this area could be decisive. The observed fracture modes were similar to those reported from studies consisting of fractographic evaluations of clinically failed zirconia crowns [41].

Through occlusal loading of the crown, the abutment material will undergo compression as well as transverse expansion as a result of Poisson's effect. The Poisson's ratio of epoxy and dentin is similar (~0.3). Therefore, the degree of bulging of the epoxy model is expected to be the same as that of teeth during mastication when subjected to the same occlusal load. The bulging causes the development of hoop stress that is largest at the crown margin. That stress state facilitates the initiation of cracks perpendicular to this hoop stress and perpendicular to the crown margin as seen in clinical failures [42,43].

The tapers of this study were 10°, 15° and 30°. The theoretically ideal taper has varied from 2 to 22 [44,45], but clinically values rarely meets these parameters [46]. A systematic review from 2015 shows that daily reported practices lie between 18.2 and 23.9 [47]. Our choice of tapers is chosen to lie in the outer limit to give an indication of the impact of the different tapers.

Previous studies of crowns produced using the computer-aided-design/computer-aided-manufacturing (CAD/CAM) technique have shown acceptable internal fit, comparable to other laboratory techniques [48,49]. In the present study the marginal cement space set in the two groups were identical, so the finding that both groups had equal marginal cement thickness was expected. The group with cement space of 60 μm had the lowest values of the cement thickness indicating good seating. Good seating combined with a small taper increases the mechanical retention and minimizes the loss of tooth substance, thereby improving clinical success [24].

An increased clearance in the group with 60 μm cement space may explain this finding [50]. The importance of the cement and cement thickness on the facture resistance are not conclusive [1,35,51,52]. The elastic modulus of the epoxy (10.5 GPa) and the glass-ionomer cement (7−8 GPa) are quite similar, while the yttria-stabilized zirconia has a higher modulus (205 GPa). The absence of a correlation between the load at fracture and internal fit in Fig. 4 can be explained by the similar characteristic of the two materials used as abutment and cement.

In general, the crown margin quality was good. This finding could explain the lack of correlation between margin flaws and the load at fracture. However, this finding is not fully in agreement with that of Thompson et al. [27] where machining defects affect the load at fracture. The preparation used in the
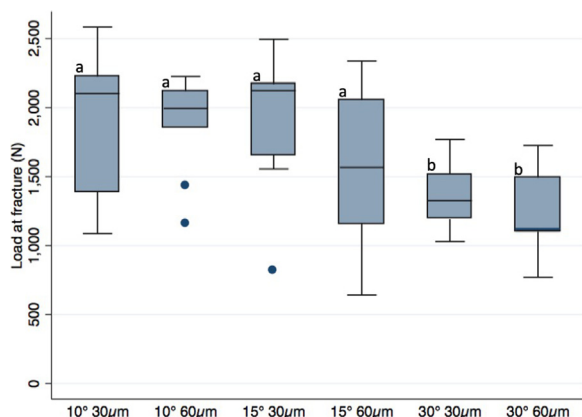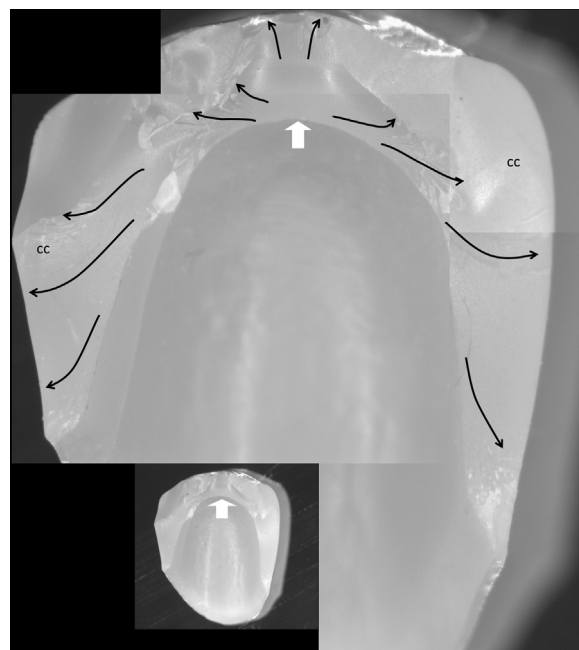
Fig. 4 – **Tukey's boxplot of the load at fracture of the different tapers and cement thickness. The groups with same superscript letters are not significantly different from each other (p > 0.05). See legend to Figure 2 for explanation of box-plot.**
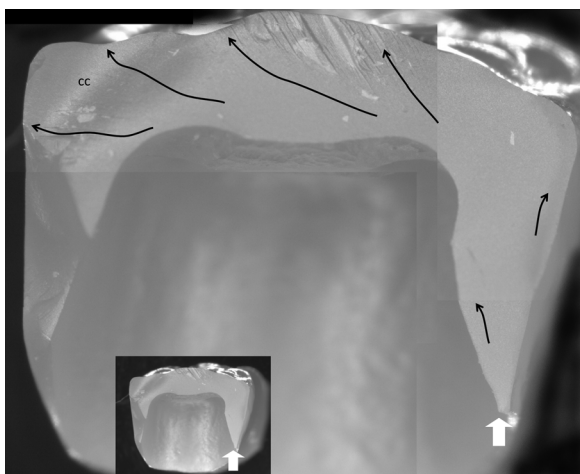
Fig. 5 – **A fractographic map for a representative crown (30°, 60 μm). The fracture origin was located at the cervical margin (white arrow). The origin is surrounded by a flat smooth area (fracture mist). The thin black arrows indicate the direction of the hackle lines radiating from the fracture mist, and the CC shows compression curls marking the far end of the fracture path where tensional force converts to compressive force.**

Fig. 6 – **A fractographic map illustrating the fracture of a representative crown (15°, 30 μm). The fracture origin was located at the internal surface of the occlusal area (white arrow). The thin black arrows indicate direction hackle lines, and the CC shows compression curl.**

single load to fracture with a constant temperature. Oral function with mastication forces at different angles and changing temperatures makes direct comparison to clinical values is difficult [53]. The tested specimens were neither exposed to artificial aging. The similar appearance of the fracture modes in the present study and those observed in clinically failed crowns indicates, however, that the stress situations are more closely related than many other *in vitro* trials with occlusal contact damages. Further studies are necessary to assess the effect of aging compared to immediate loading [54].

5.   Conclusion

Large preparation taper reduced the load at fracture of monolithic zirconia crowns. A larger pre-defined cement space improved seating but did not affect the load at fracture.

Acknowledgments

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present study was made on a single model with an even and smooth finish line. As such, universal conclusions cannot be drawn. Considering the variables present in the clinic, every preparation will have an individual appearance and there are many variables that contribute to the stress distribution in the crown [33]. The present results, however, indicate the impact of the preparation taper for ceramic crowns. The specimens that were tested in this study were made of zirconia with a high percentage of cubic crystals (49%). This reduces its flexural strength and fracture toughness when compared to the more traditional Y-TZP [9]. Nevertheless, the load at fracture in the present findings exceeds that expected from mastication forces. This study was an *in vitro* study, where there was a

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