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Monolithic zirconia crowns – wall thickness, surface treatment and load at fracture

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ABSTRACT

Purpose: The aim of this study was to evaluate the effect of wall thickness on load at fracture of monolithic zirconia dental crowns after aging.

Materials and Methods: Seventy translucent monolithic zirconia crowns (DD Bio ZX^2, Dental Direkt GmbH) were produced to fit a second upper premolar preparation with a circumferential shallow chamfer. Thirty crowns had a minimum wall thickness of 0.4 mm and 40 had 0.8 mm. TwentyAQ4 of the thick-walled crowns were glazed. The remaining crowns were polished. Ten crowns from each group functioned as controls, while the remaining were subjected to an aging procedure of alternation between dynamic loading and autoclaving. The surviving crowns were assessed for margin damages and surface wear before beeing subjected to quasi-static loading until fracture. All fractures were analyzed by fractographic methods.

Results: There were statistically significant differences among the test groups concerning the effects of aging and surface wear. All thick-walled and eight of the thin-walled crowns survived the aging procedure. All fracture origins both from dynamic and quasi-static loading were located in the cervical margin with crack propagation corresponding to cervical hoop stress as observed in clinical failures.

Conclusions: Thin-walled translucent monolithic zirconia crowns were more affected by the aging procedure than thick-walled crowns.

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KEYWORDS
Fatigue; glazing; yttria-stabilized zirconia

Introduction

Traditional 3 mol% yttria-stabilized tetragonal zirconia polycrystals (3Y-TZP) for dental restoration are opaque and require a veneer of tooth colored, but weaker, porcelain for esthetic reasons [1]. This treatment has been only moderately successful due to chipping fractures of the veneer as well as biological complications [2,3]. A new option has been made possible with more translucent and tooth colored zirconia that can be used without a veneer, termed 'monolithic', 'full-anatomic' or 'full-contour' [4–8]. The monolithic design is stronger than the traditional bi-layered design and wall thickness can be reduced [9]. Monolithic zirconia crowns may thus be used for restoring teeth without excessive removal of sound tooth substance [4,9,10]. There are no absolute requirements for monolithic restorations, but most producers indicate 0.4 mm as minimum wall thickness. Wall thickness affect crown strength *in vitro* [11,12]. It is uncertain how important wall thickness is for survival *in vivo*, but fractographic analyses of clinically failed all-ceramic crowns indicate that thinner crown margins may be more susceptible to fractures that thicker ones [13].

Monolithic zirconia can be either glazed or polished to a glossy surface. There is no evidence in favor of either of these surface treatments with regard to strength [14,15]. These crowns show high fracture resistance *in vitro*, but clinical experience has shown that they actually can break in clinical use [4]. Core fractures in zircona crowns are rarely described in clinical trials, but cases of semilunar marginal fractures and total fractures dividing the crowns in two parts have been reported [16]. This failure mode corresponds with cervical hoop stress failure mode as demonstrated *in vitro* [17,18].

The process of making the zirconia translucent and more tooth-like in appearance alters some of the

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mechanical properties compared with traditional 3 mol % Y-TZP [8]. It has been shown that initial strength is reduced, but it is not certain whether other properties, such as aging resistance or damage tolerance, are affected as well [5–7,19,20]. Furthermore, it is not evident whether direct exposure to humidity from saliva and other chemicals in the oral cavity will increase low temperature degradation (LTD) when used without veneering or glazing [21–24].

This study was initated due to several alarming reports from clinicians of immediate and early failures of monolithic crowns made with high transclucent zirconia. The aim of this study was thus to asess load at fracture for monolithic, high translucent zirconia crowns of different wall thickness. Secondly, the aim was to assess whether surface treatments, glazing or polishing, affect immediate load at fracture or the aging response from hydrothermal and dynamic loading.

Materials and methods

Sample preparation

Seventy monolithic zirconia crowns (DD Bio ZX^2, Dental Direkt GmbH, Spenge, Germany) were produced to fit a model of a prepared upper second premolar from a clinical case (Table 1). The original crown produced on this model was intended for a patient but fractured immediately in clinical use (Figure 1). The preparation had a shallow circumferential chamfer finish line, a low taper (≥5 degrees) in the most cervical region (up to 2 mm from the finish line), but no undercuts. The model was scanned (3shape D810, Copenhagen, Denmark) and the crowns designed digitally (Dental Designer 2014). The milling was performed with a five-axis milling machine (Roland DWX-50, Allerød, Denmark). Thirty crowns were produced with equal wall thickness to the original crown (0.4 mm minimum) which is minimum recommendation for the tested material for single crowns. These were polished on the outer surface with standard polishing technique (StarGloss, Edenta, Switzerland), finishing with a brush and polishing paste (Zircon-Brite Polishing Paste, DVA, Corona, USA) as recommended by the producer. Forty crowns were made with a minimum axial wall thickness of 0.8 mm. Although twice the thickness of the 0.4 crowns, the margins were not bulging. The profile change from tooth to restoration was, however, somewhat more distinct for the thick-walled crowns. The crowns were thinnest on the palatal, mesial and buccal walls. The distal wall was thicker

Table 1. Material composition (in per cent) for the tested material (DD Bio ZX2)*.

ZrO_2+HfO_2+Y_2O_3	≥99
Y_2O_3	<6
Al_2O_3	≤0.15
Other oxides	≤1.0

*According to the manufacturer (Dental Direkt GmbH, Spenge, Germany).

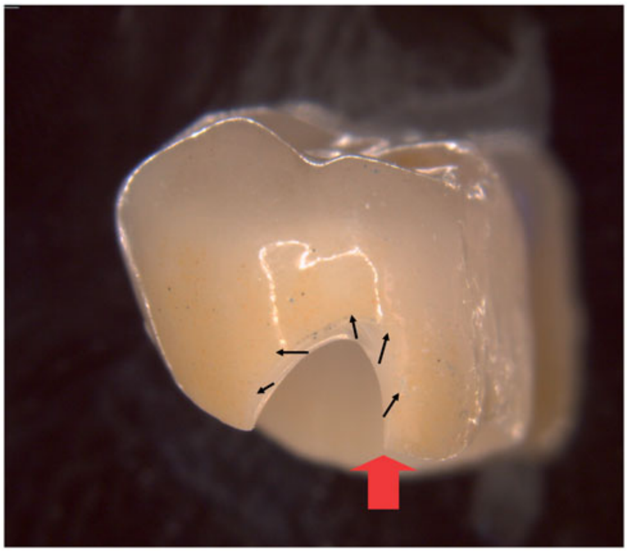

Figure 1. Clinically failed monolithic zirconia crown. The crown fractured immediately during clinical use. There was no discrepancy between tooth and model. The fracture origin (large arrow) is in the crown margin and the direction for the crack propagation is marked with small arrows.

due to the anatomy of the tooth and the distance to neighboring tooth. The occlusal surfaces were identical for all crowns (minimum 1 mm). Twenty of the thick-walled crowns were randomly chosen to be polished and the remaining 20 were glazed according to manufacturer's instructions. All crowns were inspected for cracks and other margin defects in a light microscope at 10 X magnification (Leica M205 C). Photos were taken for comparison of margins before and after the aging procedure.

Aging procedure

Ten crowns from each group were randomly chosen to function as controls and were left untreated. The remaining crowns were subjected to an aging regime with alternating heat treatment in an autoclave and chewing simulation in a pneumatic loading device (Figure 2). The crowns were attached to a brass model of the preparation with a silicone material (Aquasil Ultra LV, Dentsply DeTray GmbH, Konstanz, Germany) in order to facilitate removal and to create tensile stress (hoop stress) at the cervical margin during loading. The load was applied in the

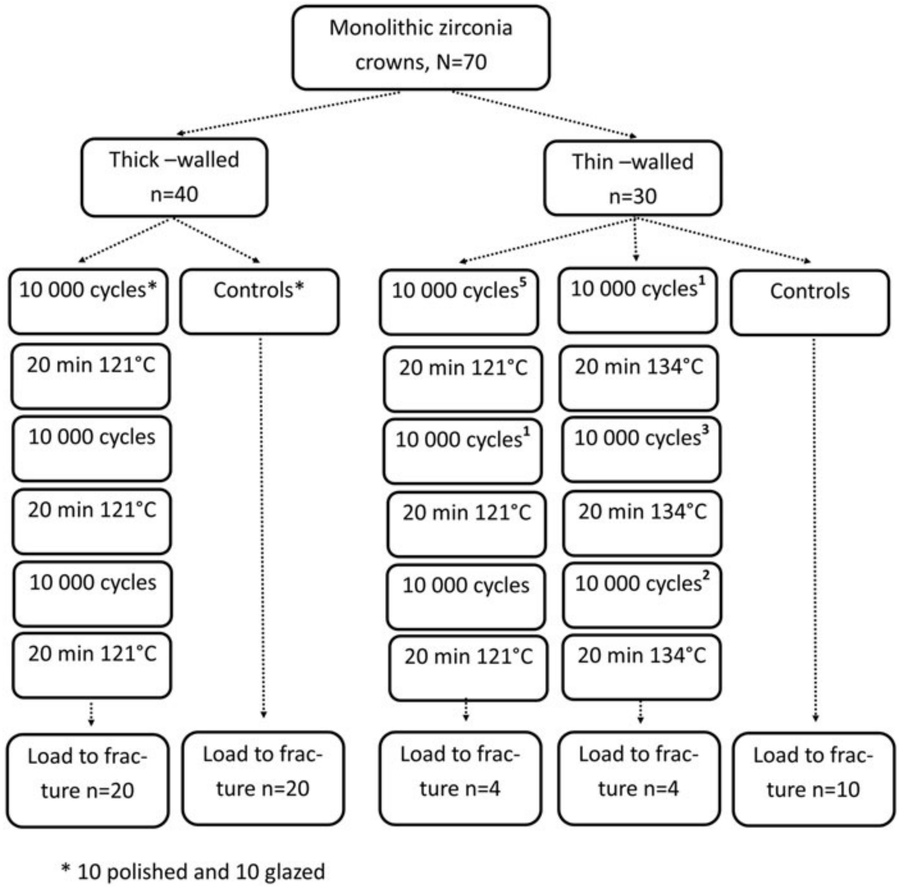

Figure 2. Test procedure. Flow chart of the test procedure for the specimens in the test groups of monolithic dental zirconia crowns. Twelve crowns did not survive the pretreatment. Superscript numbers indicate where in the procedure they fractured.

central occlusal fossa with a stainless steel ball of 6 mm in diameter with the specimens submerged in distilled water at 37 °C in a chewing simulator built on site with pneumatic piston cylinders (Festo AG & Co, Esslingen, Germany). After each chewing cycle of 10,000 cycles at alternating loads between 10 and 250 N at 1 Hz, the crowns were autoclaved at 121 °C with 2 bar pressure for 20 min before re-mounting in the chewing simulation unit. The last ten thin-walled crown were exposed to a maximum temperature of 134 °C for comparison. The crowns were air dried and inspected in a light microscope at 10× magnification between each procedure and assessed for wear, fractures and cracks. The aging cycle was repeated three times, giving a total of 30,000 load cycles and 60 min in an autoclave.

Load to fracture

All crowns surviving the aging procedure were subsequently subjected to quasi-static load until fracture in a universal testing machine (MTS 852 Minibionix II, MTS systems, Eden Prairie, US). The crowns were re-attached to the brass model with the silicone before loading. The load was applied axially in the central occlusal fossa with a stainless steel horizontal cylinder of 12 mm in diameter [18]. A rubber disk of 2 mm thickness was inserted between crown and the indenter to disperse the load evenly on the occlusal surface between the cusps. The load increased by 0.5 mm/min until fracture or upon reaching 3100 N, which was the limit of the test unit and load at fracture was recorded. The specimens were submerged in distilled water during loading. All fractures were analyzed in an optical light microscope using standard fractographic methods [25] and the fractures were compared with the clinical fracture in Figure 1 to assess the clinical relevancy. Some selected specimens were investigated further in a scanning electron microscope (Model JSM-6010PLUS/LA; JEOL, Peabody, MA, US) to assess changes in microstructure and to verify fracture origins

Statistical analysis

Statistical analyses were performed using SPSS statistics 24 (IBM; Chicago, IL, US). Non-parametric statistical method was used for comparison among groups. Kruskal-Wallis for overall comparison and Mann Whitney U-test for pair-wise comparison between groups. Spearman's Rho was used for correlation calculations. The level of significance was set to $<.05$.

Results

Twelve of the thin-walled crowns fractured during the aging procedure at 250 N, their load at fracture was set to 250 N (Figure 2). None of the thick-walled crowns fractured during the aging procedure. No margin damages were observed in any of the surviving crowns. All the glazed crowns exhibited surface wear at the loading point, with increasing severity after each test cycle (Figure 3). The polished crowns displayed no observable surface changes. There were no statistically significant differences in load at fracture or fracture modes between glazed and polished crowns and the thick walled crowns are therefore treated as one group ($p > .05$).

There was a statistically significant difference in load at fracture among the test groups (Figure 4, $p < .001$, Kruskal-Wallis). There was no statically significant difference between the thin-walled crowns autoclaved at different temperatures. Three crowns in the thick-walled aged group did not break before reaching maximum load. Their load was set to 3100 N. All fractures originated from the cervical margin, 18 of these originated from an area where small irregularities were detected prior to the testing.

Six thick-walled crowns and twelve thin-walled crowns had small marginal semilunar fracture modes similar to the clinically retrieved crown (Figures 5 and 6(a)). Twenty-six crowns had a larger semilunar fracture mode where most of the buccal or palatal wall broke off (Figure 6(b)), while the remaining 25 crowns broke in two parts through the occlusal fissure

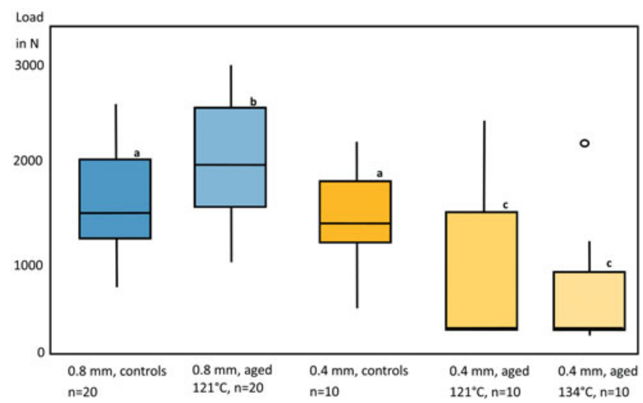

Figure 4. Box plot diagram of load at fracture during quasi-static loading. Boxes marked with the same letters are not statistically significant different from each other.

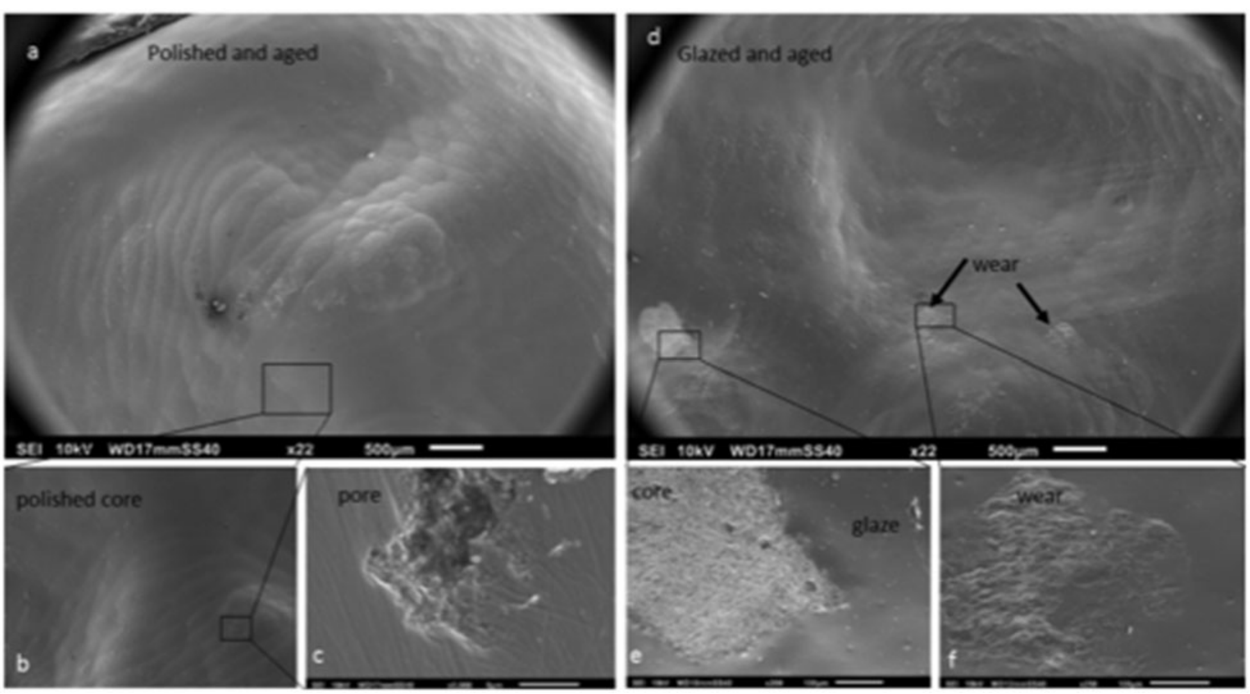

Figure 3. Occlusal wear after aging. (a) Polished occlusal surface with no signs of wear, (b) detail of polished surface, (c) pore in the polished surface. (d) Glazed occlusal surface, (e) area of insufficient glazing, (f) area of surface wear revealing the rough zirconia surface. The boxed areas in images a, b and d indicate location and size of the detailed images (b, c, e and f) at higher magnification.

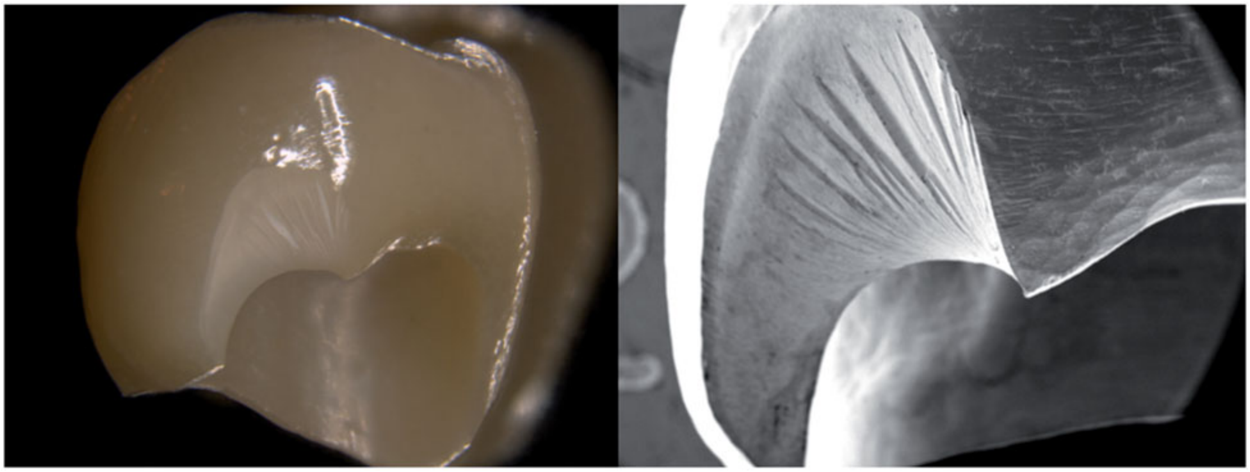

Figure 5. Failure mode. A typical semilunar margin fracture similar to the clinical case observed on a thick glazed crown in light microscope (left) and in SEM (right).

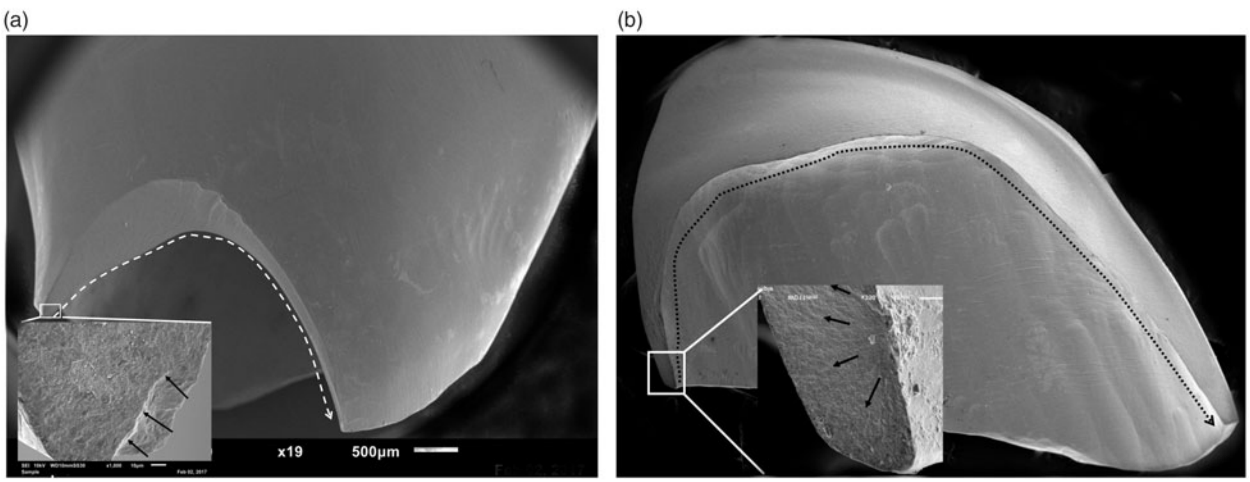

Figure 6. Semilunar fractures. Two typical semilunar fractures of thin crowns. Dotted arrows indicate crack propagation. The areas of fracture origin (white boxes) are seen at higher magnification in separate pictures with black arrows indicating critical crack. (a) A small semilunar fracture where the fracture origin was in a crack on the very margin. Probably from machining damage. (b) The fracture origin in this large semilunar fracture was at the inner wall with no apparent flaw.

groove (Figure 7). The fracture origin in the two latter categories was localized on the mesial wall where the crown height was shortest and the wall thinnest. There was no correlation between fracture mode or fracture origin and load at fracture.

No difference could be observed in the general microstructure of the crowns between aged crowns and the controls, either on the crown surface or on the fracture surfaces (Figure 8). All groups displayed fracture surfaces with mixed inter-granular and trans-granular fracture (Figure 9).

Most crowns had margin irregularities such as small chips or thinner areas, but five crowns had margin chips visible without microscope. One of these did not break during the test, however, and the others broke from regions outside the major preexisting flaw.

Discussion

The results of this study indicate that wall thickness affect load at fracture for monolithic zirconia crowns under dynamic loading. Twelve of the thin-walled crowns did not survive cyclic loading at 250 N and the strength of the remaining eight specimens decreased. The fracture modes observed in the study resemble clinically observed failures [13,16,26–29] and the fracture loads are close to or even below maximal biting force [30].

Aging procedure

Ideally, fatigue or aging should be tested by cyclic loading until fracture [31]. Very few previous studies

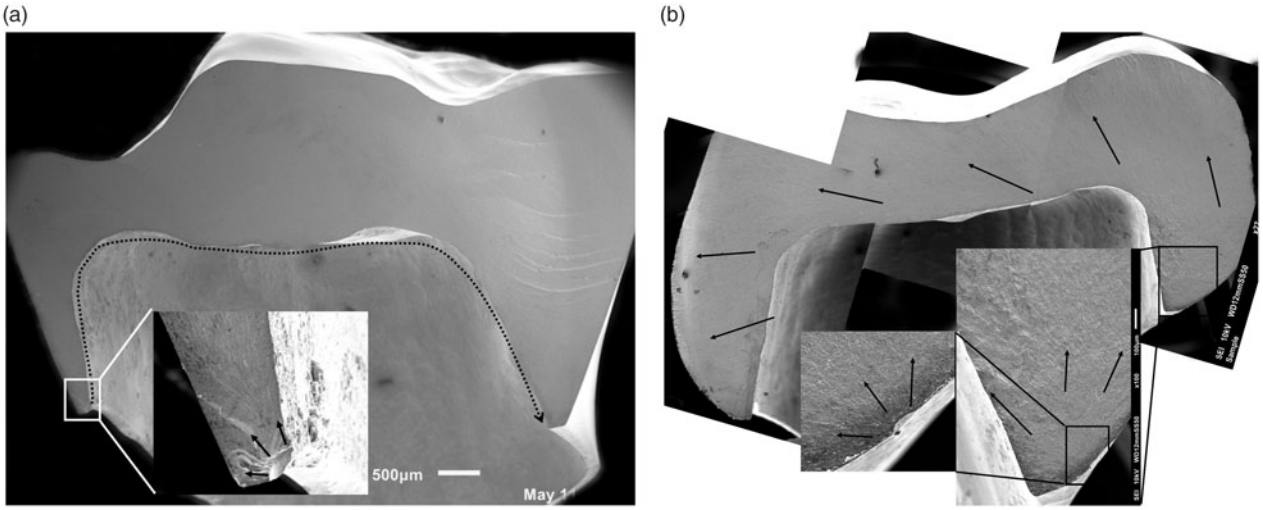

Figure 7. Total fracture. Two typical fractures dividing the crown in two parts from the mesial to the distal side. (a) A thin-walled crown with a distinct crack as the initiating flaw. (b) A thick-walled crown with fracture origin in a small defect on the outer wall, near the crown margin.

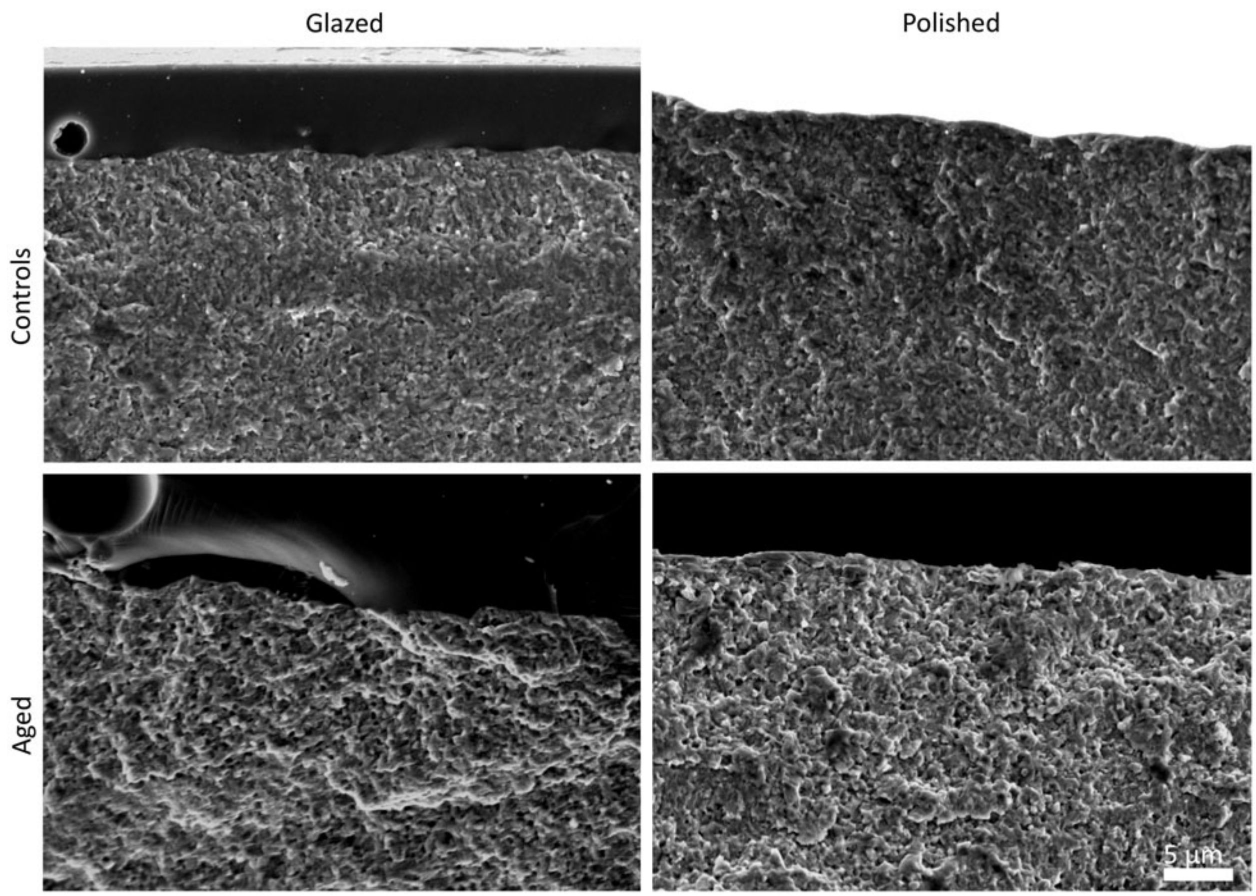

Figure 8. Microstructure. No difference in microstructure could be observed between the controls (upper Images) and the aged (lower image) crowns in either the glazed (left images) or the polished (right images) crowns.

have shown any effect of cyclic loading at sub-critical load prior to quasi-static loading. The present results show, however, that aging occurs with the method chosen in this study The findings that 12 of the thin-walled crowns fractured during the cyclic loading at 250 N, and six of them in the first round of 10,000 cycles prior to autoclaving, indicate that the mechanical loading was more detrimental than the

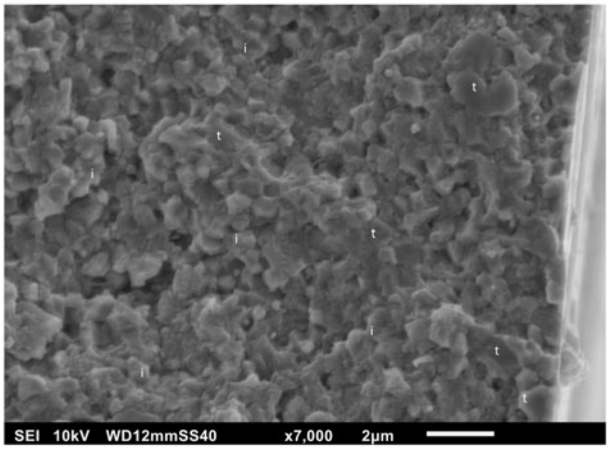

Figure 9. Fracture surface revealing both trans-granular (t) and inter-granular fracture (i).

hydrothermal exposure at both 121 °C and 134 °C. Previous studies often use higher temperatures or longer durations than in the present study in order to provoke aging [32,33]. The clinical relevancy of such extreme exposure is debated, although the chemical reaction behind it is well documented [34]. Lower temperatures and shorter durations were chosen in the present study to assess the probability of early failures which was the reason for conducting the study. The slight strengthening of the thick walled crown observed after aging can be due to an *initial t-m transformation.*

Aging of zirconia crowns has been investigated by a large number of *in vitro* trials [20,22,35–38]. However, there is no consensus regarding the method to mimic a clinically relevant aging [31]. High temperature, thermo-cycling and cyclic loading have all been used to provoke aging, either alone or in different combinations. Unfortunately, many of the studies do not have control groups and the effect of the provocation is therefore difficult to quantify. High temperatures in combination with humidity creates LTD on the surface of zirconia specimens and subsequently a reduction in fracture strength [23,36]. This has also been shown in trials on bar or disc-shaped specimens [38,39]. The clinical relevancy of this extreme aging protocol is uncertain, as this type of LTD has so far not been identified as the cause of fracture in clinical dental restorations. Cyclic loading in humid conditions has shown reduction in fracture resistance of zirconia crowns in some studies [36,40,41], but seems to have no effect in others [35,42,43]. The different studies use very different parameters with regard to frequency and duration of loading as well as size and load of indenter. The true effect is therefore difficult to evaluate and compare. The present results indicate that an alternation of cyclic loading and moderate hydro-thermal exposure gives an aging response for zirconia, although further studies are necessary to fully assess the clinical relevancy. The moderate strengthening after aging observed in the thick-walled crowns indicates that material alterations has occurred. Zirconia can display an initial increase in strength before detrimental aging occurs [39]. Since no further investigations into the microstructural changes have been performed in this study, any further explanations on this finding, will only be speculative.

The present method for aging was chosen in order to be able to subject the specimens to both hydrothermal exposure and dynamic loading since both are suspected to contribute to aging [33]. Crowns cemented securely to polymer-based abutments with a Poisson's ratio similar to dentin would be more clinically relevant [18], but the polymer abutments would be affected by the hydrothermal treatment. Furthermore, polymers may expand during prolonged submersion in water, and would thereby change the stress-situation during the dynamic loading. The silicone cement was used in order to be able to remove the crowns from the abutment between the two test settings and in order to create hoop-stress cervically without causing contact damage between abutment and crown. The fractographic analyses of the specimens that fractured during dynamic loads reveal that they did actually fracture due to hoop stress as observed in clinical failures and in the static loading [4,13,16,26], indicating that the stress situation is similar to *in vivo* situations albeit not identical.

Surface treatment

No difference in load at fracture or fracture modes was found between glazed and polished crowns. This is in contrast to a previous study using 134 °C for 5 h on disc-shaped specimens showing that glazing reduced aging resistance [44]. The effect over time must be further evaluated, since the present results represent only a short time exposure and the methods were not sufficient to detect early onset of degradation.

The finding that the polished crowns had no surface wear as opposed to the glazed ones indicate that polished crowns will give less antagonist wear compared to glazed crowns [14,15,45,46]. The glazed crowns may have a rough surface underneath the glazing. When the glaze wears off, the opposing teeth are exposed to the rough zirconia surface which will induce more wear than a polished surface [47].

Effect of wall thickness

Surprisingly, there was no difference in load at fracture between the control groups even though the thick-walled crowns had double thickness on the axial walls. All fractures originated in or near the crown margins. The crown margins were of almost equal thickness in the most cervical region. The thin-walled crowns displayed, however, significant reduction in strength after aging and more than half of the restorations fractured during the cyclic loading at only 250 N. These crowns also had margin initiated fractures. This indicates that the fracture resistance during mastication is strongly dependent on wall thickness. The reduced thickness increases the risk of slow crack growth from critical flaws.

Clinical relevance

The use of a clinical case as preparation model creates a less uniform restoration than using plastic models as is commonly used. This makes general conclusions more complicated. However, natural tooth preparation always vary greatly in design, depending on tooth anatomy and previous damages. The artificial aging procedure used in the present study creates fractures that are similar to clinical fractures. The strength of thin-walled polished zirconia crowns can decrease rapidly from cyclic loading. Furthermore, the results reveal that glazed zirconia crowns are more prone to occlusal wear. Further studies must be conducted before a conclusion can be drawn on whether or not to glaze monolithic zirconia crowns.

The cyclic loading used in this study can be compared to temporary cementation, which is not recommended for all-ceramic restorations in general. This study clearly illustrates why, since it creates hoop-stress in the cervical area where the crown is weakest.

Conclusion

The aging procedure of alternation between cyclic loading and hydro-thermal exposure affect the strength of thin-walled translucent monolithic zirconia crowns. Strength deteriorate quicker in thin-walled crowns than thick-walled crowns. Clinically relevant fatigue testing must be performed in order to fully assess the safety of the different zirconia materials available for dental restorations. Surface treatment neither affects immediate strength nor aging response. Glazed monolithic zirconia crowns are more susceptible to occlusal wear than polished crowns.

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Disclosure statement

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