Journal of Dentistry 125 (2022) 104271

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent

Fractographic analysis of 35 clinically fractured bi-layered and monolithic zirconia crowns

Anneli Skjold, Christian Schriwer, Nils Roar Gjerdet, Marit Øilo *

Department of Clinical Dentistry, Faculty of Medicine, University of Bergen, Aarstadveien 19, Bergen N-5009, Norway

ARTICLE INFO

Keywords:
Ceramics
Zirconium dioxide
Fractography
Retrieval
Crown design
Fracture origin

Objectives: The aim of this retrieval study was to analyze the fracture features and identify the fracture origin of zirconia-based single crowns that failed during clinical use.

Methods: Thirty-five fractured single crowns were retrieved from dental practices (bi-layered, $n = 15$; monolithic, $n = 20$). These were analyzed according to fractographic procedures by optical and scanning electron microscopy to identify fracture patterns and fracture origins. The fracture origins were closely examined. The crown margin thickness and axial wall height were measured.

Results: Three types of failure modes were observed: total fractures, marginal semilunar fractures, and incisal chippings. Most of the crowns (23) had fracture origins at the crown margin and seven of them had defects in the fracture origin area. The exact fracture origin was not possible to identify due to missing parts in four crowns. The crown wall thickness was 20% thinner and wall height 30% shorter in the fracture origin area compared to the opposite side.

Conclusions: The findings in this study show that fractography can reveal fracture origins and fracture modes of both monolithic and bi-layered dental zirconia. The findings indicate that the crown margin on the shortest axial wall is the most common fracture origin site.

Clinical significance: Crown design factors such as material thickness at the margin, axial wall height and preparation type affects the risk of fracture. It is important to ensure that the crown margins are even and flawless.

1. Background

Zirconia materials are used extensively for dental crowns due to an acceptable combination of esthetics and mechanical properties [1–3]. Recent developments have led to a considerable improvement in optical properties of dental zirconia. By increasing the yttria-stabilizer content to >3 mol% and thereby the proportion of cubic crystals, omitting the alumina content and adjusting the grain size, the translucency and tooth-like appearance has increased [4]. However, the necessary adjustments in material composition and grain size negatively affect the mechanical properties which in turn may limit the clinical success [5]. National or regional registries do not include reasons for failures of dental restorations in clinical practice, except for implants in some countries [6–8]. Consequently, the failure rates of different restorations or materials are unknown. Controlled clinical trials on long-term survival of dental restorations indicate that zirconia-based crowns show a relatively good longevity, with up to 95% 5-year survival rates [9–13]. The studies on zirconia crowns are relatively few and with limited sample sizes, besides most are based on first or second generation of zirconia materials, not the recent high translucent (cubic, anterior) zirconias . Furthermore, case reports and personal communication with prosthodontic specialists, general practitioners and dental technicians indicate that mechanical failures, such as zirconia framework fractures and veneering ceramic fractures, do occur quite often especially with the high translucent zirconias [9,10,14-18].

The underlying reasons for fracture of zirconia-based crowns may be due to several factors such as design, material composition or machining quality. Many *in vitro* studies have tried to investigate the effect of different preparation or crown designs on the fracture resistance [19–26]. The results are inconclusive and comparison among studies is difficult due to large differences in test methods and designs. *In vitro* studies show that there are differences among zirconia materials regarding load at fracture and margin quality [27–29]. Several studies have found that all-ceramic crowns have flaws like pores, machining defects and margin chips, but the clinical relevance of this has yet to be determined and again the studies are too different for direct comparison [30–33]. Which factors that are most important for clinical survival are not evident. At present, there are no established procedures that can cast

* Corresponding author.
E-mail addresses: anneli.skjold@uib.no (A. Skjold), christian.schriwer@uib.no (C. Schriwer), gjerdet@uib.no (N.R. Gjerdet), marit.oilo@uib.no (M. Øilo).

https://doi.org/10.1016/j.jdent.2022.104271
Received 26 May 2022; Received in revised form 12 July 2022; Accepted 25 August 2022
Available online 27 August 2022

light on why the fractures occur in clinical use as the materials in theory should be able to withstand masticatory forces.

An understanding of failure mechanisms can provide a basis for recommendations of clinical considerations regarding design and material selection. To elucidate the causes of failure of all-ceramic restorations, meticulous characterization of retrieved crowns is necessary [15]. Qualitative and quantitative fractographic examinations of clinically failed ceramic restorations have increased in later years, but the number of restorations examined are small and heterogenous [34–37]. Few zirconia-based restorations are included in these analyses [31,35, 37-40]. Furthermore, most studies are performed on bi-layered restorations with a veneering layer of porcelain where certain fracture features, such as wake hackle behind pores are more prominent than in core materials and monolithic crowns. Consequently, there is limited knowledge of how and why monolithic restorations fracture or whether zirconia-based crowns have similar fracture modes as other all-ceramic crowns.

The primary aim of this study was to identify the fracture mode and fracture origins of retrieved dental zirconia-based crowns. Furthermore, the aim was to assess which factors that contributed to clinical failure of the retrieved crowns.

2. Materials and methods

Dentists and dental technicians were invited to submit all types of all-ceramic restorations that had fractured in clinical use. The invitation was presented at various national and regional meetings and conferences where the authors gave talks about dental ceramics over the last five years. The invitations were open for all types of retrievals and submission of additional information about the restoration history or composition was voluntary since this information is not always readily available or takes time and effort to retrieve. Anonymous submissions were also accepted in case the submitters were reluctant to reveal their mistakes. The goal was to receive as many failed restorations as possible. The restorations were submitted without any patient-related information and thus raises no ethical concerns.

2.1. Sample

The submitted zirconia-based single crowns were selected for this study. Around twenty public and private dentists responded to the invitation with submission of one to six crowns each. Most restorations were received in the last three years. The retrieved crowns are thus a convenience compilation of thirty-five zirconia-based crowns that had failed during clinical use. The compilation consists of both bi-layered ($n = 15$) and monolithic ($n = 20$) zirconia crowns, from both anterior ($n = 16$) and posterior ($n = 19$) regions (Table 1). Detailed information regarding brand names, clinical function time and cement type was not available. All crowns were retrieved from individual patients, except for four monolithic anterior crowns that originated from one patient. Fracture details from these four crowns were obtained by the replica technique [40]. The dentist received detailed instructions on how to perform the impression for this procedure. The patient wished to repair the crowns instead of replacing them. All the analyzed crowns had been cemented on teeth, except for three crowns which had been cemented on implant abutments.

2.2. Preparation of the samples

The retrieved fragments were initially ultrasonically cleaned in 1% enzymatic detergent solution (Biotex, Unilever Danmark AS, Copenhagen, Denmark) for 15 min with subsequent rinsing with distilled water

Table 1
Overview of the retrieved crowns, crown type, tooth type, preparation type, failure modes, fracture origin and additional information. [a] – one premolar and two molar crowns were previously cemented on implant abutments. [b] - four monolithic incisors were retrieved from the same patient.

Crown type	Tooth type	Preparation type	Failure mode	Fracture origin	Direction of fracture	Direct cause of the fracture initiation
Bi-layer	Incisor	Chamfer	Total	Crown margin	Appr-appr	
Bi-layer	Incisor	Chamfer	Total	Crown margin	Appr-appr	
Bi-layer	Incisor	Chamfer	Total	Crown margin	Bucc-pal	
Bi-layer	Incisor	Chamfer	Total	Crown margin	Appr-appr	
Bi-layer	Incisor	Slice	Total	Crown margin	Ling-bucc	
Bi-layer	Incisor	Chamfer	Total	Crown margin	Bucc-pal	
Bi-layer	Incisor	Chamfer	Total	Crown margin	Appr-appr	
Bi-layer	Incisor	Slice	Total	Crown margin	Appr-appr	Outer defect due to manual adjustment at the crown margin
Bi-layer	Premolar	Chamfer	Total	Crown margin	Ling-bucc	
Bi-layer	Premolar [a]	Chamfer	Total	Occlusal intaglio	Occl-appr	
Bi-layer	Premolar	Chamfer	Total	Uncertain		
Bi-layer	Molar	Chamfer	Total	Crown margin	Appr-appr	
Bi-layer	Molar	Chamfer	Total	Crown margin	Appr-appr	Outer defect due to manual adjustment at the crown margin
Bi-layer	Molar	Slice	Semilunar	Crown margin	Appr-appr	
Bi-layer	Molar	Chamfer	Total	Uncertain		
Monolithic	Incisor [b]	n.n	Incisal chipping	Incisal		
Monolithic	Incisor [b]	n.n	Incisal chipping	Incisal		
Monolithic	Incisor [b]	n.n	Incisal chipping	Incisal		
Monolithic	Incisor [b]	n.n	Incisal chipping	Incisal		
Monolithic	Incisor	n.n	Total	Uncertain		
Monolithic	Canine	Chamfer	Total	Uncertain		
Monolithic	Canine	n.n	Total	Crown margin	Appr-appr	
Monolithic	Premolar	Slice	Semilunar	Crown margin	Ling-ling	
Monolithic	Premolar	Chamfer	Semilunar	Crown margin	Appr-ling	
Monolithic	Premolar	Chamfer	Semilunar	Crown margin	Ling-ling	
Monolithic	Premolar	Slice	Total	Crown margin	Appr-appr	Crown margin defect
Monolithic	Premolar	Chamfer	Total	Occlusal intaglio	Occl-appr	
Monolithic	Molar	Slice	Semilunar	Crown margin	Appr-appr	Outer defect due to manual adjustment at the crown margin
Monolithic	Molar	Slice	Total	Crown margin	Ling-bucc	Crown margin defect
Monolithic	Molar	Chamfer	Total	Crown margin	Ling-bucc	Outer defect due to manual adjustment at the crown margin
Monolithic	Molar	Slice	Semilunar	Crown margin	Ling-ling	
Monolithic	Molar	Slice	Total	Crown margin	Bucc-ling	
Monolithic	Molar	Chamfer	Total	Crown margin	Appr-bucc	Defect in material due to incomplete sintering
Monolithic	Molar [a]	Chamfer	Total	Inner axial wall		
Monolithic	Molar [a]	Chamfer	Total	Inner axial wall		Defect in material at the fracture start

before air drying. Each fractured crown was stored individually in lens paper to avoid recontamination.

2.3. Fractographic analyses

Several fracture variables were identified by thorough fractographic analysis [36,41].

Failure modes were registered as total fracture (splitting the restoration in two or more parts), semilunar fracture (small marginal fracture exposing the prepared tooth underneath) or chipping (superficial fracture, not exposing the prepared tooth). The regional location of fracture origin was registered as occlusal/incisal, marginal, or axial wall region. Furthermore, it was registered whether the origin was on the inside (intaglio) or outside surface of the crown. The direction of crack propagation (dcp) was registered as from the region of fracture origin to the end of fracture, for instance approximal-approximal or bucco-lingual. An assessment of the preparation finish line design of the abutments was made for each restoration based on the inner contour of the crown margin.

The fracture surfaces of all specimens were examined by optical microscopy (Leica M205 C, Leica Microsystems, Wetzlar, Germany) under various lighting directions. To confirm the dcp and to verify the location of the fracture origin, the specimens were further analyzed in a scanning electron microscope (Phenom XL Desktop SEM, Thermo Fisher Scientific, Waltham, MA, USA) in secondary emission mode and back scatter mode. Prior to the examination in SEM, the specimens were further cleaned in an ultrasonic bath with Dakin's solution for 10 min, rinsed with distilled water, air dried, rinsed with alcohol before air drying and sputter-coating with gold (thickness of 30 Å). Crowns with unusual material appearance were examined in secondary emission mode (SEM-SED) for analysis of material composition. One crown was excluded following this procedure as it contained mostly alumina. The crown margins at the fracture origin area were examined from both outside and inside of the crown to investigate the quality of the crown margin. Presence of introduced defects and inherent flaws such as pores and incomplete sintering, were noted. In addition, both sides of the fracture surface were examined, when the matching pieces were available. Fractographic features such as compression curls, wake hackle, arrest lines, crack branching and hackle lines were used for identification of dcp and fracture origin [36]. Images of the fracture surfaces were acquired to assemble fractographic maps where orientation, dcp and high magnification images of fracture origin and other findings were included.

2.4. Crown wall measurements

The location of origin was compared with the other similar areas of the restoration. The crown wall thickness or the zirconia core thickness were measured at three different distances from the crown margin both around the fracture origin and at the opposite end of the fracture path (Fig. 1). In addition, the axial wall height at the fracture origin was measured and compared with the axial wall height in the rest of the crown. The measurements were performed in a microscope imaging software (LAS X, Leica Microsystems, Wetzlar, Germany) on digital photos taken by optical microscopy (Leica M205 C, Leica Microsystems, Wetzlar, Germany).

3. Statistics

This study is a descriptive study of the retrieved restorations. The number of specimens was too low for statistical comparison among groups with sufficient power.

4. Results

Overall examination of the crowns showed three failure modes: total fracture (n = 26), semilunar fracture at the crown margin (n = 5) and incisal chipping (n = 4) (Fig. 2 and Table 1). All bi-layered crowns except for one, had failed by total fracture of the core framework. In the monolithic crowns, all three failure modes were observed. In 16 out of 35 crowns, droplets or smears of veneering and glazing materials was observed on the intaglio surface of the crown margins.

Fractographic analysis identified four different areas of fracture origins: at the crown margin (23), at the intaglio axial wall surface (2), at the occlusal intaglio surface (2) and at the outer incisal surface (4) (Figs. 3–6, Tables 1 and 2). For 13 of the crowns with fracture origin at the crown margin, the location was in the approximal region of the crown. The exact fracture origins of four of the crowns were impossible to identify due to missing fragments but they were still included as the fracture mode in general could be identified. Three crowns that were cemented on implant abutments had fracture origin at the crowns' intaglio surface. For eight of the crowns observed defects were likely fracture initiators (Figs. 7 and 8).

Assessment of the crown design showed that the crown margin was 20% thinner around the fracture origin compared to the opposite end of the fracture path. The axial wall height at the fracture origin was on average 30% shorter than the opposing wall.

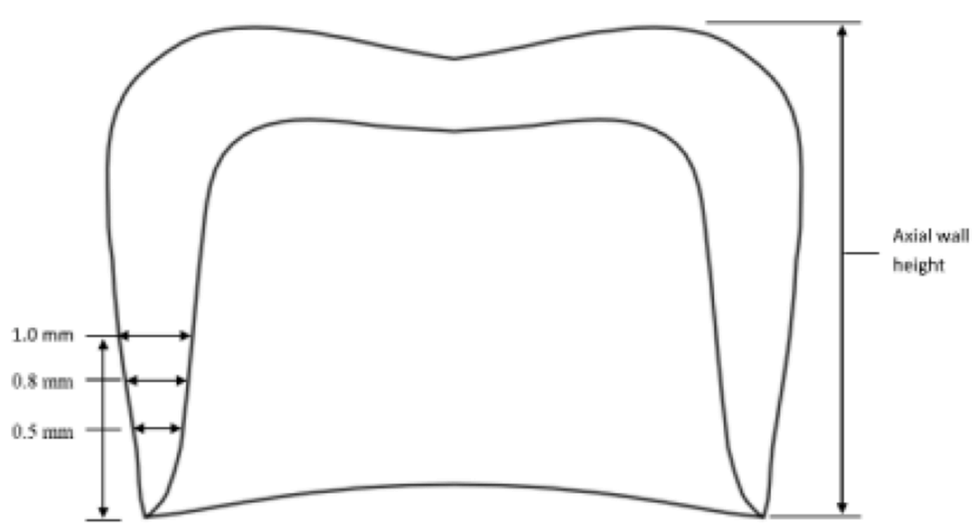

Fig. 1. A schematic cross-section illustration of the measurement points for crown margin thickness and axial wall height.

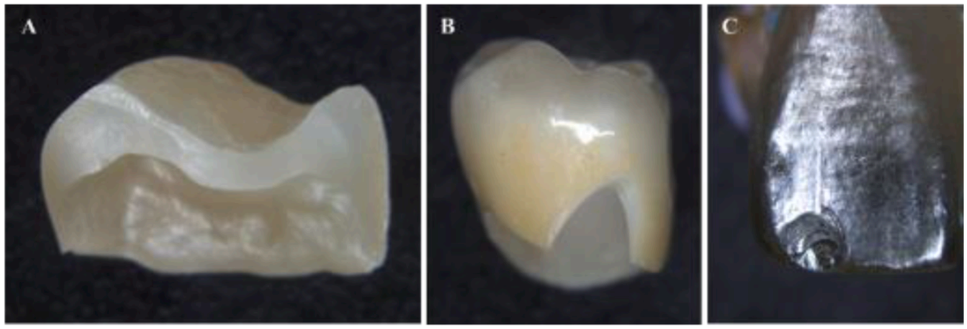

Fig. 2. Three failure modes that were observed in retrieved crowns. A: total fracture, shown on one half of a totally fractured monolithic molar crown B: semilunar fracture at the crown margin (marginal chipping), shown on monolithic premolar crown. C: incisal chipping shown on an gold coated epoxy replica of a monolithic incisal crown.

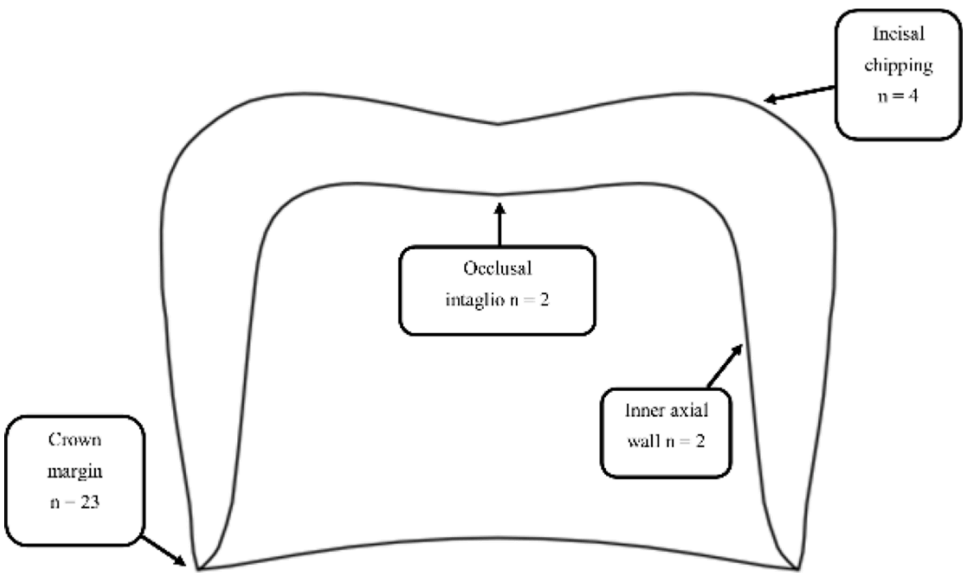

Fig. 3. A schematic figure of cross-section of a crown. Fractographic analysis identified four different fracture origin areas. N = number of crowns in each area.

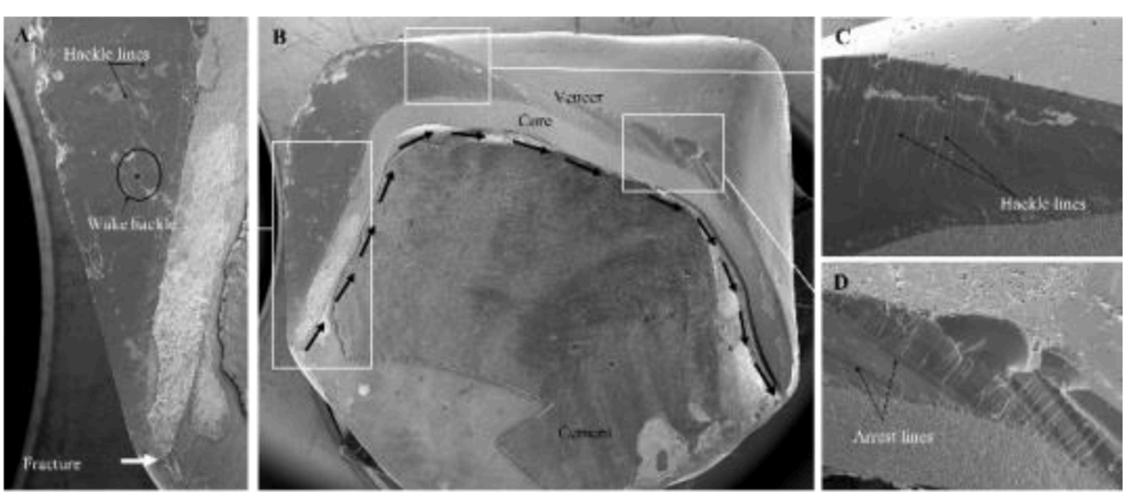

Fig. 4. A fractographic map of a veneered incisor zirconia crown (SEM , secondary emission mode).The largest part of the crown is the buccal half shown in the central image (B, × 10). Black arrows indicate the direction of crack propagation. The white boxes indicate the size and location of the detail images (A, C and D × 30). The fracture origin is at the approximal region of the crown margin shown in A. Fractographic features that are visible in the veneer layer are wake hackle (A), hackle lines (C, magnification x30) and crack arrest lines (D, magnification x30).

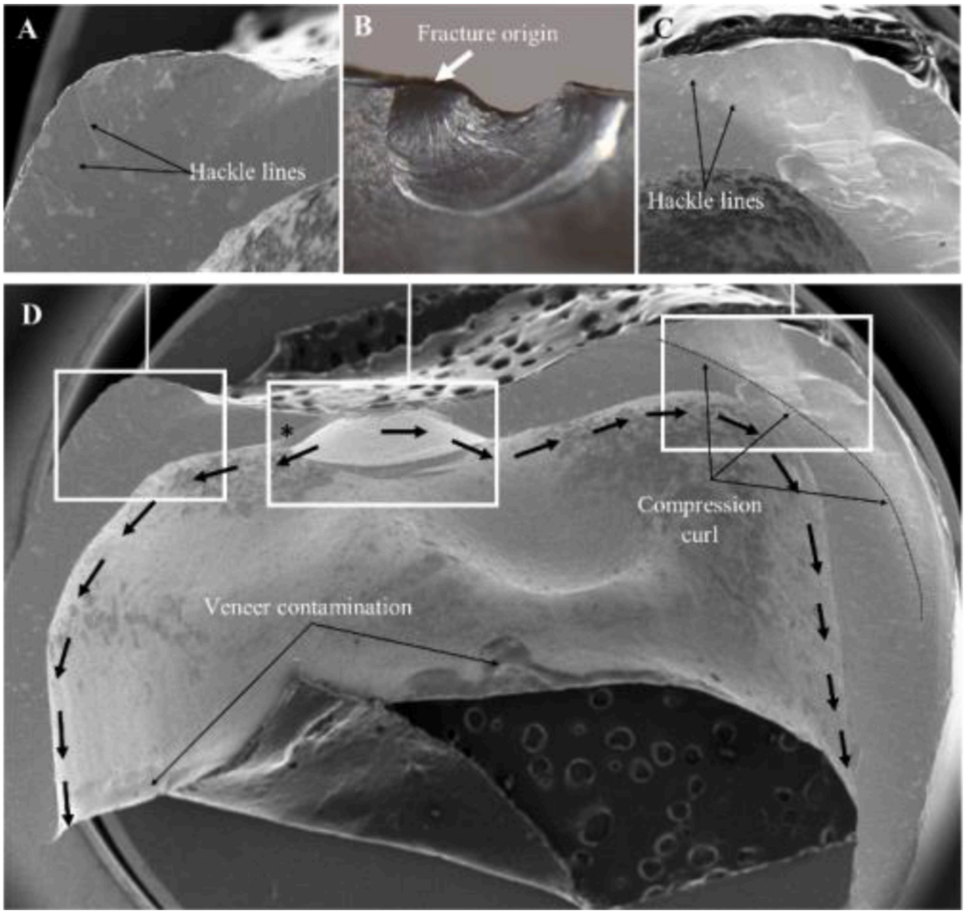

Fig. 5. A fractographic map of a monolithic molar zirconia crown with fracture origin at the crown occlusal intaglio surface. The main image D (×15) shows the largest part of the retrieved crown. Black arrows show the direction of crack propagation. The white boxes indicate the size and location of the detail images. Image B (×20) is taken from the inside of the crown showing the fracture origin (white arrow). Fractographic features that are visible are hackle lines (A and C, ×80) and compression curl (D). The occlusal thickness was 0.310 mm near fracture origin area (* in D). Veneer contamination is visible at the crown margin (D).

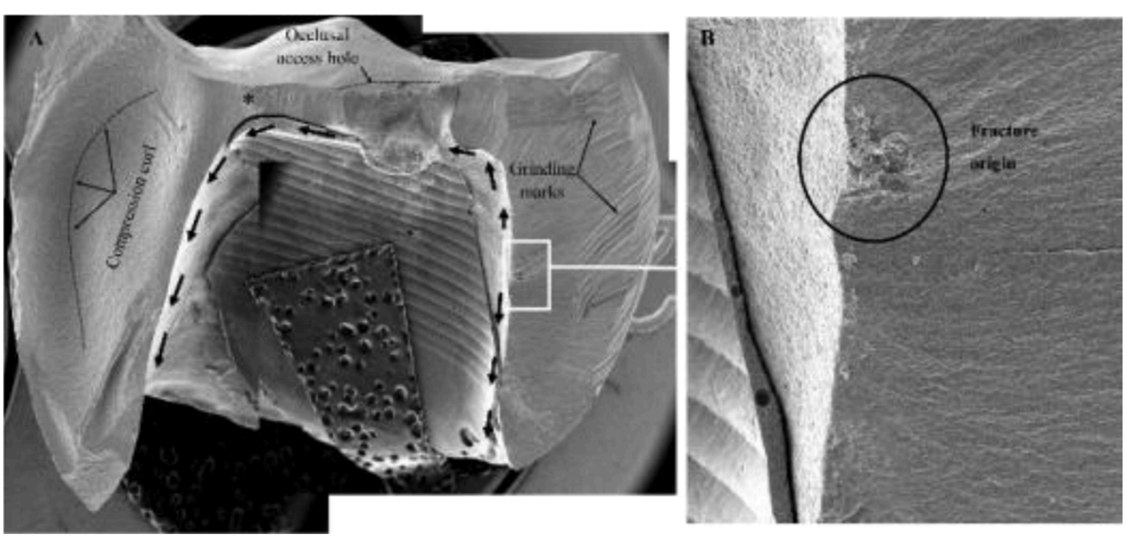

Fig. 6. A fractographic map of a monolithic molar zirconia crown that was cemented on implant abutment (A, ×20 magnification). The crack propagation is show with black arrows. Fracture originated at the crown inner axial wall. Local defect possibly caused during sintering acted as fracture-initiator (B, ×50 magnification). Compression curl and occlusal access hole are visible in A. Thin occlusal thickness compared to axial wall thickness (0,385 mm) at the area marked with * in A). Grinding marks due to post-failure adjustment of the sharp edges are visible (A).

5. Discussion

The results show that fractography can be used to determine fracture origins and crack propagation for zirconia-based restorations even without veneering porcelain. Given the higher strength of dental zirconia, it could be assumed that fracture modes of zirconia-based restorations differ from the more fragile alumina and glass-ceramic ones. The present result show, however, that the fracture modes resemble other all-ceramic restorations [31,35,42-46]. The findings can thus be used as a guide to develop more clinically relevant *in vitro* test methods for all-ceramic crowns in general as the fracture modes differ from those observed in most "crunch-the-crown" studies [47,48].

Table 2
Summary of the fracture origins for anterior and posterior crowns within the two different crown fabrication types. [a]-crowns that were cemented on implant abutment. [b]- retrieved from the same patient.

Different groups Crown fabrication type	Tooth type	Fracture origin Crown margin	Occlusal intaglio	Inner axial wall	Outer incisal	Uncertain	Sum
Bi-layered	Anterior	8	0	0	0	0	8
	Posterior	4	1[a]	0	0	2	7
Monolithic	Anterior	1	0	0	4[b]	2	7
	Posterior	10	1	2[a]	0	0	13

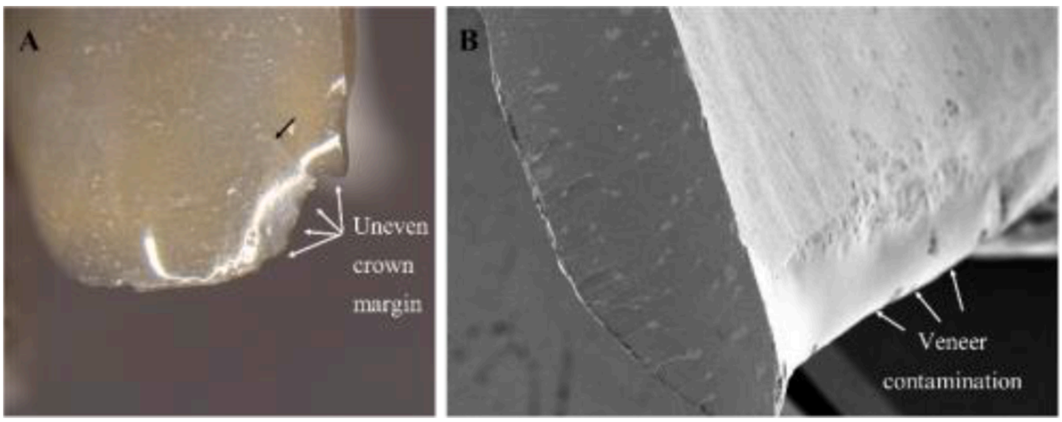

Fig. 7. Close up images of two different fractured crowns with fracture origin at the crown margin. A: visible-to-eye defect (white arrows) at the crown margin close to fracture origin area (×10, buccal view). Also, an incomplete fracture line is visible (black arrow). B: A monolithic crown with contamination of veneering material on the inside of the crown margin (white arrows) (×100).

Fractographic analyses of clinically failed all-ceramic dental restorations provide an approach to determination of failure origin [49,50]. The findings of this study indicates that the crown margins in zirconia-based crowns is highly prone to fracture initiation. This indicates that the crown margin design is of great importance for fracture resistance. Brittle fractures in ceramics can be described by a weakest link model with regards to flaw population and microstructure features around the fracture origin. Mastication forces on the occlusal surfaces of a dental crown can cause tensile stress at the crown margins [48]. Very thin margins or defects will increase the potential for stress concentration exceeding the fracture resistance. The defects may be flaws within the material created during sintering processes or margin defects introduced by machining or post-production processing, such as manual adjustment of the crown margin (Figs. 7 and 8). In this study, not all observed margin defects served as fracture initiators. However, seven out of 23 crowns with fracture origin at the crown margin, had defects at the crown margin that most likely acted as fracture initiators. Similar observations were made in a previous study, which also showed that crowns had pores, contamination, or incomplete sintering acting as fracture initiators [31]. This indicates that extra attention and care should be taken during CAD/CAM machining and any post-production adjustment of the zirconia crowns.

Seventeen of the 23 crowns with fracture origins at the crown margin, had thinner margins in the fracture origin area compared with the opposite side. The thin crown margins indicate that the abutment teeth had slice preparation or very shallow chamfers. However, due to the lack of detailed information of the abutment teeth, these are only assumptions of the preparation designs. It may also be that the dental technician had made the crown unnecessary thin. The crown margin thickness in some of the crowns was uneven, varying from very thin (<0.1 mm) to relatively thick (>0.5 mm). In such crowns, the fracture started in the thinner part of the crown margin. The effect of thin crown margins becomes even more apparent in the bi-layered crowns, where the thickness of the zirconia core material is even thinner due to the veneering layer. The observed difference in failure modes between bi-layered and monolithic zirconia crowns supports this assumption. Almost all bi-layered crowns had total fracture while all three fracture modes were present in the monolithic crowns. Several *in vitro* studies on material thickness indicate that a material thickness of 0.5 mm is a critical thickness for monolithic zirconia crowns [51–57]. *In vitro* studies examining alternative design of crown margin such as outer collar at crown margin to increase the margin thickness showed higher fracture strength of the zirconia crowns [19,58-60]. It is important to bear in mind that unnecessary deep chamfer preparations may jeopardize the pulp vitality and must thus be avoided.

The height of the crown wall is usually shorter in the approximal area, where the crown margin curves due to the gingival papilla. Most of the crowns in the present compilation had fracture origins in the shortest region of the axial crown wall indicating the this is a stress concentration area. An *in vitro* study examining the effects of margin curvature on load at fracture of ceramic crowns showed that increased curvature in the proximal margins reduced load at fracture [34,61]. The results indicate that a leveling of the crown margin may increase the fracture resistance, but on the other hand this may cause a retraction of the dental papilla and subsequently the alveolar bone. Furthermore, a leveled crown margin requires more tooth substance removal and can thus compromise the tooth and the pulp vitality more than necessary. The pros and cons must be considered in each individual case.

The observed contaminations of veneering and glazing materials on the inner side of the crown margins illustrates the complexity of the dental technical procedures as has been shown previously [31]. The surplus material can lead to increased hoop stress at the crown margin during seating and cementation as the restorations are made to fit perfectly with approximately 50 μm cement space marginally. Furthermore, veneer or glaze on the inside will have a negative effect on cement flow during cementation and may thus increase the hoop stress even more or result in incomplete seating [31,35,38]. Furthermore, tension at the crown margin may be caused by dentine distortion during occlusal loading [16,48,62]. None of the three crowns in this study that were cemented on implant abutments had fracture origin at the crown

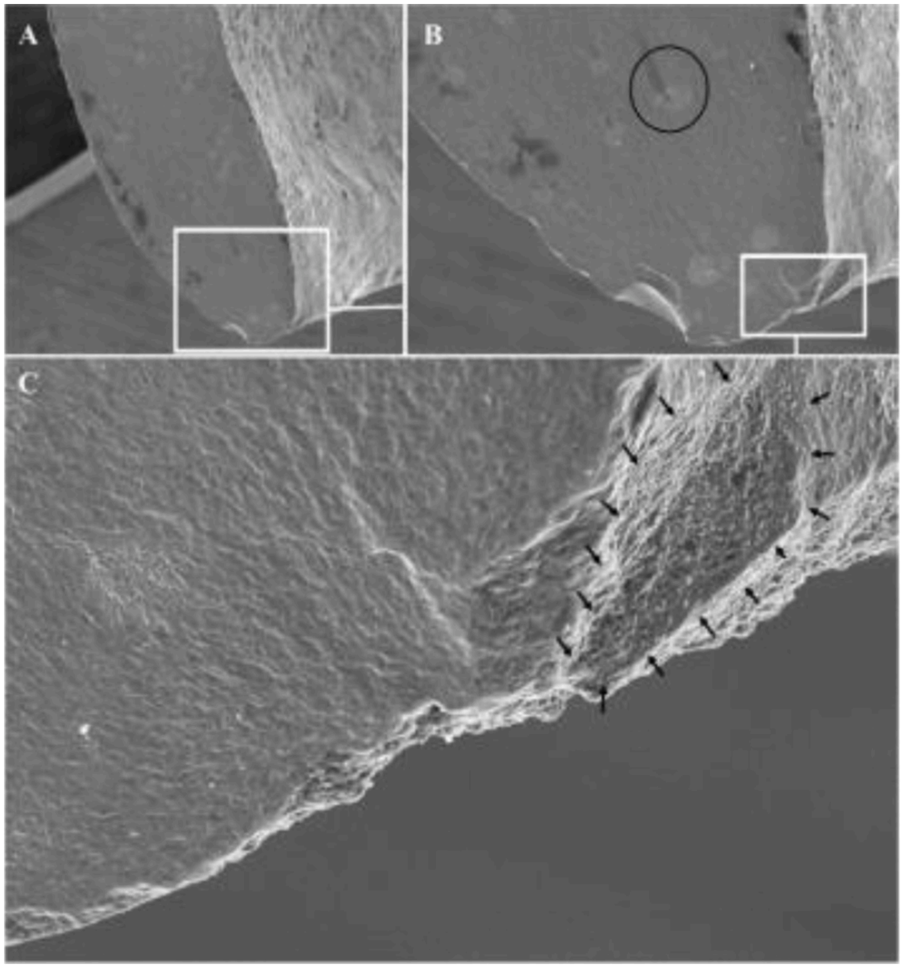

Fig. 8. Close up images of a monolithic crown with fracture origin at the crown margin (A, ×70 magnification). A defect in the zirconia material due to incomplete sintering acted as a fracture initiator (black arrows, C, ×700). Another defect within the material is shown with black circle (B, ×200).

margin. *In vitro* studies have shown that the fracture strength of all-ceramic crowns depend on the flexibility of the supporting structure indicating that tooth supported and implant supported restorations are subjected to different stress distribution during occlusion [63]. The absence of abutment flexure may result in different fracture modes. The limited number of crowns in the present compilation makes it impossible to draw a conclusion, but previous observations of implant-based restorations are in accordance with these [16].

There were no bi-layered crowns with veneer chipping retrieved in this study, although it is known that veneer chipping is the predominant technical complication [10,64,65]. This might be because *in situ* crowns with only veneer chipping failures are most often repaired rather than replaced. Furthermore, these crowns are difficult to remove without destroying them totally. Four monolithic crowns recorded with incisal chipping were retrieved from the same patient which has known parafunction, and these cannot be counted as four independent cases. However, this indicates that chipping failures do occur in zirconia despite the high strength. The fact that these crowns were incisor crowns strongly indicates that they were of a newer generation of high translucency zirconia, which has shown to have a lower fracture toughness than the first generation 3mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) [66]. X-ray diffraction or Raman analyses could possibly detect more accurately which type of zirconia each crown was made of. As zirconia is often suggested as the solution to patients with severe parafunction, such as grinding, clenching or bruxism, it is important to know which type of zirconia to choose in each case. The lack of detailed information the dentists share when submitting crowns, indicates that many are unaware of the distinctions. Typical information was "This is a zirconia crown. It was cemented a couple of years ago and broke last month without any special events" or they wrote the generic brand name without specifying which type. Most producers have between three to five different types of zirconias of different compositions and amount of yttria stabilizer to choose from.

This study included relatively few specimens, but it is still a large compilation for this type of retrieval analyses. Surprisingly few dentists responded to our invitations, given that many have told us they often see fractured restorations in their practice and asked how to avoid it. On the other hand, some submitted several restorations. This indicates that there is a high degree of underreporting. Personal communications with dental technicians suggested that they were reluctant to submit fractured restorations they had received for their collaborating dentists as they considered it to be the dentists' responsibility. Due to the limited number of specimens, the present results do not represent the variety of fractures occurring in clinical practice and does not fully elucidate the complexity of this clinical challenge. Future clinical retrieval studies need to include more detailed information regarding material composition, processing methods, cementation technique, time in function, gender of patient and occlusal forces. A mandatory registry of failed dental restorations would improve the possibilities for this type of retrieval analyses tremendously. As it is now, most busy private practitioners do not see the benefits of spending their precious time on careful removal and collection of fractured crowns and disinfecting the parts before sending them to a research laboratory. Future clinical trials of all-ceramic restorations should likewise always include a thorough failure analysis including fractography if applicable.

6. Conclusion

The crown margin is a critical region for both monolithic and bi-layered crowns as most fracture originates here. Care should be taken during post-production adjustments to avoid introducing critical flaws, especially in the approximal region where the crown walls are often both shortest and thinnest and thus most susceptible for stress concentrations surpassing the fracture resistance threshold.

Retrieval analyses are useful for understanding clinical failures of dental restorations. Fractographic analysis of zirconia-based dental restoration reveals both the fracture mode and possible reasons for fracture. The lack of systematic reporting or registration of failed dental restorations limits our ability to learn from our mistakes. A standardized procedures for failure analysis of clinical retrievals as well as *in vitro* tests would increase the possibility of comparison among studies and over time.

The manuscript Fractographic analysis of 35 clinically fractured bi-layered and monolithic zirconia crowns has been a collaborative work.

Anneli Skjold has been the main author of this project, and has contributed in all steps form the planning, data collection interpretation and writing of the manuscript. Skjold and Øilo have performed the fractographic analyses together. Skjold has written the first draft and made the figures in collaboration with Marit Øilo.

Christian Schriwer has contributed with planning of study design, collection of samples and the clinical interpretation of the findings as well as preparation of the manuscript

Nils Roar Gjerdet has contributed with the planning of the study, interpretation of the data as well as revisions of the manuscript.

Marit Øilo is the corresponding author, and has contributed at all stages of this study from planning of the study, collection of samples, fractography, interpretation to preparation and submission of the manuscript

Dear editor

The authors declare no conflicts of interest with any on the products or methods mentioned in the manuscript “Fractographic analysis of clinically fractured bi-layered and monolithic zirconia crowns”

Best regards Marit Øilo and co-authors.

References

[1] I. Denry, J.R. Kelly, State of the art of zirconia for dental applications, Dent. Mater. 24 (2008) 299–307, https://doi.org/10.1016/j.dental.2007.05.007.

[2] F. Komine, M.B. Blatz, H. Matsumura, Current status of zirconia-based fixed restorations, J. Oral Sci. 52 (4) (2010) 531–539, https://doi.org/10.2334/josnusd.52.531.

[3] T. Miyazaki, T. Nakamura, H. Matsumura, S. Ban, T. Kobayashi, Current status of zirconia restoration, J. Prosthodont. Res. 57 (4) (2013) 236–261, https://doi.org/10.1016/j.jpor.2013.09.001.

[4] G. Pekkan, K. Pekkan, B.Ç. Bayindir, M. ÖZcan, B. Karasu, Factors affecting the translucency of monolithic zirconia ceramics: a review from materials science perspective, Dent. Mater. J. 39 (1) (2020) 1–8, https://doi.org/10.4012/dmj.2019-098.

[5] F. Zhang, M. Inokoshi, M. Batuk, J. Hadermann, I. Naert, B. Van Meerbeek, J. Vleugels, Strength, toughness and aging stability of highly-translucent Y-TZP ceramics for dental restorations, Dent. Mater. 32 (12) (2016) e327–e337, https://doi.org/10.1016/j.dental.2016.09.025.

[6] F.J. Burke, P.S. Lucarotti, Ten-year outcome of crowns placed within the General Dental Services in England and Wales, J. Dent. 37 (1) (2009) 12–24, https://doi.org/10.1016/j.jdent.2008.03.017.

[7] A.K. Antalainen, M. Helminen, H. Forss, G.K. Sandor, J. Wolff, Assessment of removed dental implants in Finland from 1994 to 2012, Int. J. Oral Maxillofac. Implants 28 (6) (2013) 1612–1618, https://doi.org/10.11607/jomi.3277.

[8] R. Naemi, H.R. Barikani, L. Shahmoradi, Dental implant quality registries and databases: a systematic review, J. Educ. Health Promot. 10 (2021) 214.

[9] T.A. Sulaiman, A.A. Abdulmajeed, A. Delgado, T.E. Donovan, Fracture rate of 188695 lithium disilicate and zirconia ceramic restorations after up to 7.5 years of clinical service: a dental laboratory survey, J. Prosthet. Dent. 123 (6) (2020) 807–810, https://doi.org/10.1016/j.prosdent.2019.06.011.

[10] B.E. Pjetursson, N.A. Valente, M. Strasding, M. Zwahlen, S. Liu, I. Sailer, A systematic review of the survival and complication rates of zirconia-ceramic and metal-ceramic single crowns, Clin. Oral. Implants Res. 29 (Suppl 16) (2018) 199–214, https://doi.org/10.1111/clr.13306.

[11] U.S. Beier, I. Kapferer, H. Dumfahrt, Clinical long-term evaluation and failure characteristics of 1,335 all-ceramic restorations, Int. J. Prosthodont. 25 (1) (2012) 70–78.

[12] C. Larsson, A. Wennerberg, The clinical success of zirconia-based crowns: a systematic review, Int. J. Prosthodont. 27 (1) (2014) 33–43, https://doi.org/10.11607/ijp.3647.

[13] I. Sailer, N.A. Makarov, D.S. Thoma, M. Zwahlen, B.E. Pjetursson, All-ceramic or metal-ceramic tooth-supported fixed dental prostheses (FDPs)? A systematic review of the survival and complication rates. Part I: single crowns (SCs), Dent. Mater. 31 (6) (2015) 603–623, https://doi.org/10.1016/j.dental.2015.02.011.

[14] N.C. Lawson, K. Frazier, A.K. Bedran-Russo, S. Khajotia, J. Park, O. Urquhart, A. Council on Scientific, Zirconia restorations: an American Dental Association Clinical Evaluators Panel survey, J. Am. Dent. Assoc. 152 (1) (2021) 80–81, https://doi.org/10.1016/j.adaj.2020.10.012, e2.

[15] C. Monaco, M. Caldari, R. Scotti, A.C.R. Group, Clinical evaluation of 1,132 zirconia-based single crowns: a retrospective cohort study from the AIOP clinical research group, Int. J. Prosthodont. 26 (5) (2013) 435–442, https://doi.org/10.11607/ijp.3099.

[16] M. Øilo, D. Arola, Fractographic analyses of failed one-piece zirconia implant restorations, Dent. Mater. 34 (6) (2018) 922–931, https://doi.org/10.1016/j.dental.2018.03.018.

[17] T.L. Hansen, C. Schriwer, M. Øilo, H. Gjengedal, Monolithic zirconia crowns in the aesthetic zone in heavy grinders with severe tooth wear – An observational case-series, J. Dent. (2018) 14–20, https://doi.org/10.1016/j.jdent.2018.01.013.

[18] A.A. de Almeida Jr., O.F. Munoz Chavez, B.R. Galvao, G.L. Adabo, Clinical fractures of veneered zirconia single crowns, Gen. Dent. 61 (6) (2013) e17–e21.

[19] A. Skjold, C. Schriwer, M. Øilo, Effect of margin design on fracture load of zirconia crowns, Eur. J. Oral Sci. 127 (1) (2019) 89–96, https://doi.org/10.1111/eos.12593.

[20] M. Zimmermann, G. Egli, M. Zaruba, A. Mehl, Influence of material thickness on fractural strength of CAD/CAM fabricated ceramic crowns, Dent. Mater. J. 36 (6) (2017) 778–783, https://doi.org/10.4012/dmj.2016-296.

[21] G. Mitov, Y. Anastassova-Yoshida, F.P. Nothdurft, C. von See, P. Pospiech, Influence of the preparation design and artificial aging on the fracture resistance of monolithic zirconia crowns, J. Adv. Prosthodont. 8 (1) (2016) 30–36, https://doi.org/10.4047/jap.2016.8.1.30.

[22] S. Shahrbaf, R. van Noort, B. Mirzakouchaki, E. Ghassemieh, N. Martin, Fracture strength of machined ceramic crowns as a function of tooth preparation design and the elastic modulus of the cement, Dent. Mater. 30 (2) (2014) 234–241, https://doi.org/10.1016/j.dental.2013.11.010.

[23] M. Ferrari, A. Giovannetti, M. Carrabba, G. Bonadeo, C. Rengo, F. Monticelli, A. Vichi, Fracture resistance of three porcelain-layered CAD/CAM zirconia frame designs, Dent. Mater. 30 (7) (2014) e163–e168, https://doi.org/10.1016/j.dental.2014.02.004.

[24] M. Rosentritt, V. Preis, M. Behr, S. Krifka, In-vitro performance of CAD/CAM crowns with insufficient preparation design, J. Mech. Behav. Biomed. Mater. 90 (2019) 269–274, https://doi.org/10.1016/j.jmbbm.2018.10.002.

[25] S. Miura, S. Kasahara, S. Yamauchi, H. Egusa, Effect of finish line design on stress distribution in bilayer and monolithic zirconia crowns: a three-dimensional finite element analysis study, Eur. J. Oral Sci. 126 (2) (2018) 159–165, https://doi.org/10.1111/eos.12402.

[26] Z. Zhang, T. Sornsuwan, C. Rungsiyakull, W. Li, Q. Li, M.V. Swain, Effects of design parameters on fracture resistance of glass simulated dental crowns, Dent. Mater. 32 (3) (2016) 373–384, https://doi.org/10.1016/j.dental.2015.11.018.

[27] A. Skjold, C. Schriwer, N.R. Gjerdet, M. Øilo, Effect of artificial aging on high translucent dental zirconia: simulation of early failure, Eur. J. Oral Sci. 128 (6) (2020) 526–534, https://doi.org/10.1111/eos.12739.

[28] N.C. Lawson, C.A. Jurado, C.T. Huang, G.P. Morris, J.O. Burgess, P.R. Liu, K. E. Kinderknecht, C.P. Lin, D.A. Givan, Effect of surface treatment and cement on fracture load of traditional zirconia (3Y), translucent zirconia (5Y), and lithium disilicate crowns, J. Prosthodont. 28 (6) (2019) 659–665, https://doi.org/10.1111/jopr.13088.

[29] K.V. Cardoso, G.L. Adabo, E. Mariscal-Muñoz, S.G. Antonio, J.N. Arioli Filho, Effect of sintering temperature on microstructure, flexural strength, and optical properties of a fully stabilized monolithic zirconia, J. Prosthet. Dent. 124 (5) (2020) 594–598, https://doi.org/10.1016/j.prosdent.2019.08.007.

[30] E.D. Rekow, Digital dentistry: the new state of the art - Is it disruptive or destructive? Dent. Mater. 36 (1) (2020) 9–24, https://doi.org/10.1016/j.dental.2019.08.103.

[31] M. Øilo, G.D. Quinn, Fracture origins in twenty-two dental alumina crowns, J. Mech. Behav. Biomed. Mater. 53 (2016) 93–103, https://doi.org/10.1016/j.jmbbm.2015.08.006.

[32] G.D. Quinn, L.K. Ives, S. Jahanmir, Machining cracks in finished ceramics, Fractogr. Adv. Ceram. Ii. 290 (2005) 1–13, https://doi.org/10.4028/www.scientific.net/KEM.290.1.

[33] D. Rekow, V.P. Thompson, Near-surface damage–a persistent problem in crowns obtained by computer-aided design and manufacturing, Proc. Inst. Mech. Eng. [H] 219 (2005) 233–243, https://doi.org/10.1243/095441105x9363.

[34] M. Øilo, K. Kvam, K. Reisegg, N.R. Gjerdet, The effects of margin curvature on load at fracture of ceramic crowns, Int. J. Prosthodont. 28 (4) (2015) 357–359, https://doi.org/10.11607/ijp.4191.

[35] M. Øilo, A.D. Hardang, A.H. Ulsund, N.R. Gjerdet, Fractographic features of glass-ceramic and zirconia-based dental restorations fractured during clinical function, Eur. J. Oral Sci. 122 (3) (2014) 238–244, https://doi.org/10.1111/eos.12127.

[36] S.S. Scherrer, U. Lohbauer, A.Della Bona, A. Vichi, M.J. Tholey, J.R. Kelly, R. van Noort, P.F. Cesar, ADM guidance-ceramics: guidance to the use of fractography in failure analysis of brittle materials, Dent. Mater. 33 (6) (2017) 599–620, https://doi.org/10.1016/j.dental.2017.03.004.

[37] Z. Pang, A. Chughtai, I. Sailer, Y. Zhang, A fractographic study of clinically retrieved zirconia–ceramic and metal–ceramic fixed dental prostheses, Dent. Mater. 31 (10) (2015) 1198–1206, https://doi.org/10.1016/j.dental.2015.07.003.

[38] Q. Du, M.V. Swain, K. Zhao, Fractographic analysis of anterior bilayered ceramic crowns that failed by veneer chipping, Quintessence Int. 45 (5) (2014) 369–376, https://doi.org/10.3290/j.qi.a31536.

[39] O.D. Moraguez, H.W. Wiskott, S.S. Scherrer, Three- to nine-year survival estimates and fracture mechanisms of zirconia- and alumina-based restorations using standardized criteria to distinguish the severity of ceramic fractures, Clin. Oral Investig. 19 (2015) 2295–2307, https://doi.org/10.1007/s00784-015-1455-y.

[40] S.S. Scherrer, J.B. Quinn, G.D. Quinn, H.W.A. Wiskott, Fractographic ceramic failure analysis using the replica technique, Dent. Mater. 23 (11) (2007) 1397–1404, https://doi.org/10.1016/j.dental.2006.12.002.

[41] G. Quinn, NIST recommended practice guide: fractography of ceramics and glasses. Special publication 960-16e, National Institute of Standards and Technology, Washington, DC, 2016. Fractography of Ceramics and Glasses, 3rd Edition (nist.gov).

[42] Y. Alfawaz, Zirconia crown as single unit tooth restoration: a literature review, J. Contemp. Dent. Pract. 17 (5) (2016) 418–422, https://doi.org/10.5005/jp-journals-10024-1865.

[43] T. Traini, R. Sorrentino, E. Gherlone, F. Perfetti, P. Bollero, F. Zarone, Fracture strength of zirconia and alumina ceramic crowns supported by implants, J. Oral Implantol. 41 (2015) 352–359, https://doi.org/10.1563/AAID-JOI-Dd-13-00142. Spec No.

[44] N. Nordahl, P. Vult von Steyern, C. Larsson, Fracture strength of ceramic monolithic crown systems of different thickness, J. Oral Sci. 57 (3) (2015) 255–261, https://doi.org/10.2334/josnusd.57.255.

[45] C. Johansson, G. Kmet, J. Rivera, C. Larsson, Vult Von Steyern, Fracture strength of monolithic all-ceramic crowns made of high translucent yttrium oxide-stabilized zirconium dioxide compared to porcelain-veneered crowns and lithium disilicate crowns, Acta Odontol. Scand. 72 (2) (2014) 145–153, https://doi.org/10.3109/00016357.2013.822098.

[46] M. Øilo, N.R. Gjerdet, Fractographic analysis of all-ceramic crowns: a study of 27 clinically fractured crowns, Dent. Mater. 29 (2013) e78–e84, https://doi.org/10.1016/j.dental.2013.03.018.

[47] J.R. Kelly, P. Benetti, P. Rungruanganunt, A.D. Bona, The slippery slope: critical perspectives on *in vitro* research methodologies, Dent. Mater. 28 (1) (2012) 41–51, https://doi.org/10.1016/j.dental.2011.09.001.

[48] M. Øilo, K. Kvam, J.E. Tibballs, N.R. Gjerdet, Clinically relevant fracture testing of all-ceramic crowns, Dent. Mater. 29 (8) (2013) 815–823, https://doi.org/10.1016/j.dental.2013.04.026.

[49] U. Lohbauer, G. Amberger, G.D. Quinn, S.S. Scherrer, Fractographic analysis of a dental zirconia framework: a case study on design issues, J. Mech. Behav. Biomed. Mater. 3 (8) (2010) 623–629, https://doi.org/10.1016/j.jmbbm.2010.07.004.

[50] J.Y. Thompson, K.J. Anusavice, A. Naman, H.F. Morris, Fracture surface characterization of clinically failed all-ceramic crowns, J. Dent. Res. 73 (12) (1994) 1824–1832, https://doi.org/10.1177/00220345940730120601.

[51] M. Zimmermann, A. Ender, A. Mehl, Influence of CAD/CAM fabrication and sintering procedures on the fracture load of full-contour monolithic zirconia crowns as a function of material thickness, Oper. Dent. 45 (2) (2020) 219–226, https://doi.org/10.2341/19-086-L.

[52] Y.H. Tekin, Y. Hayran, Fracture resistance and marginal fit of the zirconia crowns with varied occlusal thickness, J. Adv. Prosthodont. 12 (5) (2020) 283–290, https://doi.org/10.4047/jap.2020.12.5.283.

[53] P. Weigl, A. Sander, Y. Wu, R. Felber, H.C. Lauer, M. Rosentritt, In-vitro performance and fracture strength of thin monolithic zirconia crowns, J. Adv. Prosthodont. 10 (2) (2018) 79–84, https://doi.org/10.4047/jap.2018.10.2.79.

[54] W. Bomicke, P. Rammelsberg, T. Stober, M. Schmitter, Short-term prospective clinical evaluation of monolithic and partially veneered zirconia single crowns, J. Esthet. Restor. Dent. 29 (1) (2017) 22–30, https://doi.org/10.1016/j.dental.2013.09.004.

[55] Y. Zhang, J.J.W. Lee, R. Srikanth, B.R. Lawn, Edge chipping and flexural resistance of monolithic ceramics, Dent. Mater. 29 (12) (2013) 1201–1208, https://doi.org/10.1016/j.dental.2013.09.004.

[56] K. Nakamura, A. Harada, R. Inagaki, T. Kanno, Y. Niwano, P. Milleding, U. Örtengren, Fracture resistance of monolithic zirconia molar crowns with reduced thickness, Acta Odont. Scand. 73 (8) (2015) 602–608, https://doi.org/10.3109/00016357.2015.1007479.

[57] K. Nakamura, M. Mouhat, J.M. Nergard, S.J. Laegreid, T. Kanno, P. Milleding, U. Örtengren, Effect of cements on fracture resistance of monolithic zirconia crowns, Acta Biomater. Odontol. Scand. 2 (1) (2016) 12–19, https://doi.org/10.3109/23337931.2015.1129908.

[58] J.H. Kim, J.H. Park, Y.B. Park, H.S. Moon, Fracture load of zirconia crowns according to the thickness and marginal design of coping, J. Prosthet. Dent. 108 (2) (2012) 96–101, https://doi.org/10.1016/S0022-3913(12)60114-0.

[59] M.K. Saha, S. Bansal, V. Pathak, S. Bhardwaj, A. Chauhan, A.S. Nirwan, A comparative evaluation of fracture load of monolithic and bilayered zirconia crowns with and without a cervical collar: an *in vitro* study, Med. Pharm. Rep. 92 (2) (2019) 172–177, https://doi.org/10.15386/MPR-985.

[60] M. Øilo, K. Kvam, N.R. Gjerdet, Load at fracture of monolithic and bilayered zirconia crowns with and without a cervical zirconia collar, J. Prosthet. Dent. 115 (5) (2016) 630–636, https://doi.org/10.1016/j.prosdent.2015.11.017.

[61] N.R. Silva, E. Bonfante, B.T. Rafferty, R.A. Zavanelli, L.L. Martins, E.D. Rekow, V. P. Thompson, P.G. Coehlo, Conventional and modified veneered zirconia *vs.* metalloceramic: fatigue and finite element analysis, J. Prosthodont. 21 (6) (2012) 433–439, https://doi.org/10.1111/j.1532-849X.2012.00861.x.

[62] B.R. Lawn, J.J. Lee, Analysis of fracture and deformation modes in teeth subjected to occlusal loading, Acta Biomater. 5 (6) (2009) 2213–2221, https://doi.org/10.1016/j.actbio.2009.02.001.

[63] M.T. Yucel, I. Yondem, F. Aykent, O. Eraslan, Influence of the supporting die structures on the fracture strength of all-ceramic materials, Clin. Oral Invest. 16 (4) (2012), https://doi.org/10.1007/s00784-011-0606-z.

[64] M.N. Aboushelib, A.J. Feilzer, C.J. Kleverlaan, Bridging the gap between clinical failure and laboratory fracture strength tests using a fractographic approach, Dent. Mater. 25 (3) (2009) 383–391, https://doi.org/10.1016/j.dental.2008.09.001.

[65] A. Örtorp, M.L. Kihl, G.E. Carlsson, A 5-year retrospective study of survival of zirconia single crowns fitted in a private clinical setting, J. Dent. 40 (6) (2012) 527–530, https://doi.org/10.1016/j.jdent.2012.02.011.

[66] Y. Zhang, B.R. Lawn, Novel zirconia materials in dentistry, J. Dent. Res. 97 (2) (2018) 140–147, https://doi.org/10.1177/0022034517737483.