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Fractographic features of glass-ceramic and zirconia-based dental restorations fractured during clinical function

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Fractures during clinical function have been reported as the major concern associated with all-ceramic dental restorations. The aim of this study was to analyze the fracture features of glass-ceramic and zirconia-based restorations fractured during clinical use. Twenty-seven crowns and onlays were supplied by dentists and dental technicians with information about type of cement and time in function, if available. Fourteen lithium disilicate glass-ceramic restorations and 13 zirconia-based restorations were retrieved and analyzed. Fractographic features were examined using optical microscopy to determine crack initiation and crack propagation of the restorations. The material comprised fractured restorations from one canine, 10 incisors, four premolars, and 11 molars. One crown was not categorized because of difficulty in orientation of the fragments. The results revealed that all core and veneer fractures initiated in the cervical margin and usually from the approximal area close to the most coronally placed curvature of the margin. Three cases of occlusal chipping were found. The margin of dental all-ceramic single-tooth restorations was the area of fracture origin. The fracture features were similar for zirconia, glass-ceramic, and alumina single-tooth restorations. Design features seem to be of great importance for fracture initiation.

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The use of all-ceramic restorations has increased since the introduction of high-strength core ceramics as an alternative to metal cores (1). The stiff and brittle ceramic materials are susceptible to fracture, in particular when exposed to tensile stresses (2). Clinical trials of all-ceramic restorations reveal that fracture of the restorations is one of the main reasons for failure (3). Studies on zirconia-based restorations have mostly reported problems with chipping of the veneering ceramic (4, 5), but some core fractures have also been reported (6, 7).

Clinical trials usually report only fracture rates and no assessment of reasons for fracture or description of the fractures. The fracture mechanisms of all-ceramic crowns are not yet fully understood, and simulations of clinical fractures in vitro has proved to be difficult (8, 9). Fractographic analyses of ceramic restorations fractured in clinical use reveal the fracture origin, the fracture path, and perhaps the reason for fracture (10, 11). So far, the published fractographic analyses of dental restorations have been case reports (11–14) and one larger systematic report on alumina crowns (15). Systematic fractographic analyses of glass-ceramic and zirconia single-tooth restorations are not currently available. It is therefore not evident whether alumina, glass-ceramic, and zirconia crowns have similar fracture features.

The aim of this study was to analyze the fracture features of retrieved dental single-tooth restorations of zirconia or glass-ceramics in order to determine the crack initiation site and crack propagation.

Material and methods

Twenty-seven fractured all-ceramic single-tooth restorations were collected and analyzed. The restorations were submitted by dentists and dental technicians in Norway. We announced our plans in several lectures and seminars and encouraged participants to send the fractured restorations to us. The remaining fragments were carefully removed by the dentist, intact or by splitting with a burr if necessary, packed in soft packaging material to avoid damage, and sent to us by post. Any damage done during removal, such as that caused by drilling or handling with metal instruments, was distinguishable by optical microscopy. Only surfaces that were not destroyed by handling were used in the analyses to ensure that the original fractures were the object of interest. The dentists supplied the information available on time since cementation, type of cement used, and any special events that may have occurred. Unfortunately, information regarding materials used in core, veneer, and cement was incomplete. Information on how the crowns were produced was not included, so it is uncertain whether they were pressed, soft machined, or hard machined. The crowns were inspected visually to determine the shape and orientation of the crown, taking care not to destroy any surfaces (Fig. 1). The crowns were cleansed with ethylenediaminetetraacetic acid (EDTA) and then placed in distilled water in an ultrasonic bath for 5 min to remove debris. Further cleansing was undertaken with acetone if necessary. Analyses were performed in an optical light microscope (Leica DM IRM; Leica, Wetzlar, Germany) with a gradual increase in magnification.

The fracture surfaces of each restoration were documented with photographs of fractographic features. The photographs were mounted together in fractographic maps in order to determine the crack propagation through the crown. The starting point and crack propagation were determined using standard fractographic methods (15, 16). Each crown was thoroughly searched for wake hackle and other fractographic features in both veneer and core. The crack propagation was determined according to the direction of these features. If there were several fracture paths, contact damage, and chipping, the direction of the hackle was used to determine the primary and secondary fractures according to standard fractographic methods. Defects were observed at the fracture origin in many of the specimens. As it was not possible to determine, by optical microscopy, whether the defects were the cause or a result of the fracture, the defects were not included in the analyses.

The analyses were performed twice by three observers. Two of the observers worked in pair whilst interpreting the fractures. In cases of discrepancy all three observers carried out a final analysis together. This was necessary in three cases in which it was impossible to determine the start as a result of missing parts and in one additional crown with two starting points.

Results

The results of the analyses of the individual crowns are listed in Table 1 and are summarized in Table 2. For three of the restorations it was impossible to determine crack propagation and initiation point and therefore these restorations were excluded from further analyses. The remaining restorations displayed fracture features that indicated the origin and the direction of the fracture.

The 14 glass-ceramic restorations were difficult to analyze because of the very tortuous fracture surfaces made by the lithium disilicate crystals that camouflage the fracture features (Fig. 2). Some only revealed hackle in the glazing, but usually crack arrest lines and compression curls could be used to confirm the fracture path indicated by the miniature hackle in the glazing. These features were visible in the optical stereomicroscope, but difficult to photograph. A scanning electron microscope (Zeiss, Oberkochen, Germany) was used to illustrate the findings for one specimen (Fig. 3).

The 13 zirconia restorations, on the other hand, revealed distinct fracture features in both core and veneer material (Fig. 4). In some cases the veneer had partially delaminated from the zirconia core during fracture, which complicated the analyses. It was necessary to map all secondary fractures first, and then assess the direction of the main fracture.

Overall, crack propagation from one approximal surface to the other was evident in 11 restorations. Ten restorations had fractures that started on the palatal side of the crown (Fig. 5). Five of these were located only on the palatal side as semilunar fractures of the palatal flange of the crowns. Three zirconia crowns had been removed as a result of chipping of veneering ceramic only. These chippings were clearly caused by occlusal contact damage. One of these had visible grinding grooves at the occlusal surface at the start of the chip. In all the restorations with core–veneer fracture, the catastrophic fractures had initiated in the core material in the cervical margin. The area of initiation was usually located in the approximal region or at the point where the axial crown wall was shorter than in the adjoining areas.

Discussion

In spite of the high flexural strength of zirconia, clinical core fractures do occur also in single-unit restorations. All the retrieved samples had fracture features similar to those found in a previous study on alumina-based crowns, except for three with chipping damage only

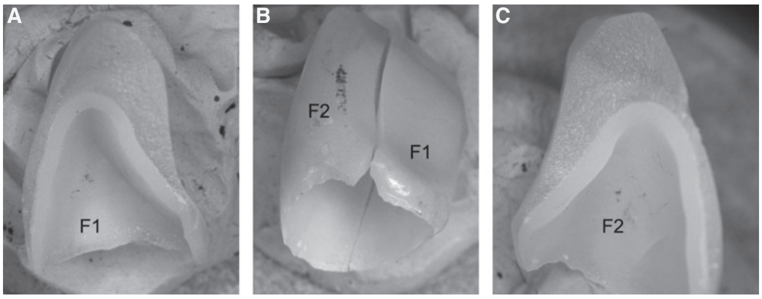

Fig. 1. The two fragments (F1 and F2) of the retrieved upper-incisor zirconia crown. (A) Overview over the fracture surface of fragment 1. (B) Repositioned fragments, lingual view, one small piece is missing. (C) The fracture surface of fragment 2.

Table 1

Overview of the crowns retrieved, core material, tooth type, time in function, type of cement used, fracture modes, and additional information

Material	Tooth type	Cement	Years in function	Fracture origin	Direction of fracture	Additional information
Glass-ceramic	Canine	Adhesive	7	Cervical	Appr-appr	
Glass-ceramic	Incisor	Adhesive	9	Cervical	Palatal	Crack observed for 3 yr
Glass-ceramic	Incisor	Adhesive	9	Cervical	Appr-appr	Attrition
Glass-ceramic	Incisor	Adhesive	2	Cervical	Palatal	
Glass-ceramic	Incisor veneer	Adhesive	3.5	*	*	Too small parts
Glass-ceramic	Premolar	Adhesive	7	Cervical	Appr-appr	Erosion
Glass-ceramic	Premolar	Adhesive	*	Cervical	Appr-appr	
Glass-ceramic	Premolar	Adhesive	2	Cervical	Palatal semilunar	
Glass-ceramic	Premolar	*	*	Cervical	Appr-appr	
Glass-ceramic	Molar onlay	Adhesive	3	Marginal	Appr-appr	Crack observed over 2 yr
Glass-ceramic	Molar onlay	Adhesive	*	Marginal	*	
Glass-ceramic	Molar	Adhesive	2.5	Cervical	Appr-appr	Two starts
Glass-ceramic	Molar	Adhesive	5.5	Cervical	Pal-Bucc	
Glass-ceramic	*	*	*	Origin is missing	*	Endodontically treated
Zirconia	Incisor	Zinc phosphate	*	Cervical	Palatal semilunar	
Zirconia	Incisor	Adhesive	3	Cervical	Appr-appr	Attrition
Zirconia	Incisor	Adhesive	0.02	Cervical	Palatal	
Zirconia	Incisor	Adhesive	2.5	Cervical	Palatal	
Zirconia	Incisor	Adhesive	2.5	Cervical	Appr-appr	From palatal side
Zirconia	Incisor	*	2.1	Occlusal	Distal chip	
Zirconia	Molar	Glass ionomer	6	Cervical	Appr-appr	
Zirconia	Molar	*	2.5	Cervical	Palatal semilunar	
Zirconia	Molar	*	*	Cervical	Palatal semilunar	
Zirconia	Molar	*	*	Occlusal	Chipping	
Zirconia	Molar	Zinc phosphate	0.5	Cervical	Palatal semilunar	
Zirconia	Molar	*	5	Cervical	Appr-appr	
Zirconia	Molar	Adhesive	0.02	Occlusal	Chipping	Contact damage

Appr-appr, From one approximal surface to the other approximal surface; Pal-Bucc, From the palatal side to the buccal side.
*Data not available or difficult to determine.

Table 2

Summary of results

Material	Number of restorations	Mean time in function (yr)	Fracture origin	Region of origin
Glass-ceramic	14	5	Cervical	Approximal 7 Palatal 4 Uncertain 3
Zirconia	13	2.4	Cervical 10 Occlusal 3	Approximal 4 Palatal 6 Chip 3

(15). In that study, all the fracture origins were located at the margins. It seems that design issues are of greater importance than the material regarding fracture initiation and fracture modes. It is likely that the present study underestimates the number of restorations that chipped (5). Chipping of veneering ceramics may have several causes and chipped crowns may often be adjusted in situ by the clinician. In the present study, the chipping fracture originated from occlusal damage. The low number of samples with chipping damage analyzed in this study makes conclusions regarding cause and effect impossible.

The location of the fracture origins indicates that core fractures are initiated by tension at the cervical margin. It is not evident from the present findings whether cervical tension is caused by wedging forces, hoop forces from cementation, or tooth flexure. The dentin has a Poisson ratio of approximately 0.3, which may cause bulging or distortion of the dentine cervically during occlusal loading (2, 17–19). Ceramics are weak in tension (2) and the expanding dentin may create sufficient tensile stress to cause core fracture (20, 21). Furthermore, high cementation force or excess cement inside the crown may induce an unfavorable stress distribution (22). Most of the restorations had the fracture origin in the approximal area. As a result of tooth anatomy and gingival contour, the axial crown wall is usually shorter in the approximal area than in the buccal or palatal areas. The curved margin of the crown will cause stress to be concentrated at the highest point of this curve or at any flaws present in the region. The finding that many fractures propagated along the shortest route from one approximal side to the other indicates that alterations in thickness and geometry of the core in the approximal region may be of importance. Owing to the limited number of restorations and the large variation in anatomy, it is difficult to assess the effect of crown geometry, tooth geometry, or cementation modes on fracture rates. Further studies with scanning electron microscopy of the fracture origins are planned to evaluate the presence and type of flaws at the fracture origin and whether or not these are the cause of fracture initiation.

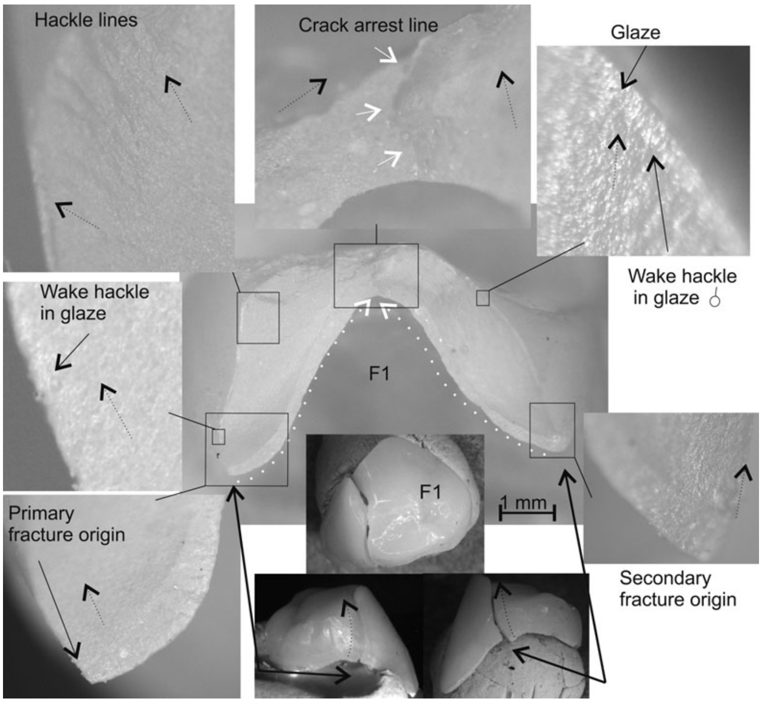

Fig. 2. Typical fractographic map of a retrieved glass-ceramic crown. The direction of fractographic features is marked with black arrows (F1). The tail of the wake hackle (pore with tail) indicates fracture propagation. The hackle lines follow the direction of the crack. The crack propagation is marked with long white dotted arrows. Small white arrows indicate a crack arrest line. Note that this crown has two fracture lines. The crown has a very thin layer of glazing and an inner layer of opaque ceramic, which is probably applied to cover a dark abutment. The black boxes on the fracture surface of F1 indicate the size and location of the connected higher-magnification images.

Previous laboratory studies are ambiguous regarding the effect of dimension and design of the cervical margin on fracture strength (23–26). As a result of different study designs, the results are difficult to interpret with regard to clinical relevance. Finite element analyses have shown higher tensile stress at the contact area underneath the loading device than in the cervical areas (27, 28). Small alterations in margin design and axial wall height in the models affect the distribution of stress (24, 29, 30). Localized reduction of axial wall height as in a restoration with a curved crown margin gives a totally different stress distribution than a crown with a leveled crown margin (24, 29). The finite element models of tooth–cement–core–veneer structures are complex and require accurate data for the different materials in order to be correct, data which are not readily available at present. Computer models or laboratory tests of simulated crowns based on simple cylindrical shapes may not adequately represent genuine crowns.

Most in-vitro fracture tests of crowns reveal fractures induced by contact damage from the loading device (24, 31–34), leading to the assumption that occlusal load causes ceramic crowns to fracture from the point of contact and also created a basis for many in-vitro tests and finite element analyses (9, 35). The failure modes found both in the present and in previous studies of crowns fractured during clinical function (12, 15, 36, 37) do not match the fracture modes found in vitro (24, 25, 34, 38–40). Contact damage was seen as

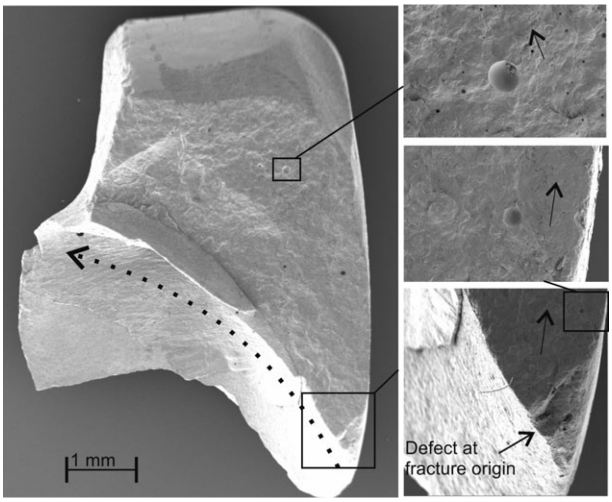

Fig. 3. Scanning electron microscopy images of one fragment of a glass-ceramic crown. The dotted arrow indicates the general direction of the fracture. Small black arrows indicate the direction of the individual fractographic features. There is a defect at the fracture origin. Further studies are needed to assess whether this was causing the fracture or was caused by the fracture. Note the tortuous surface and the lack of distinct fractographic features. The black boxes on the fracture surface indicate the size and location of the connected higher-magnification images.

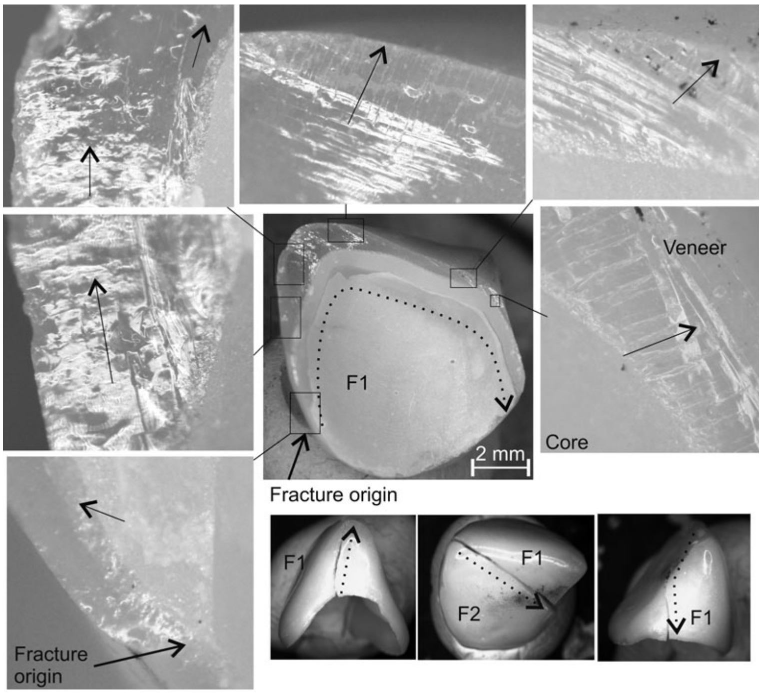

Fig. 4. Typical fractographic map of a zirconia incisor crown fractured into two fragments. The black dotted arrows indicate the general crack propagation through the crown. Small black arrows indicate the direction of the individual fractographic features, such as wake hackle and hackle lines. The black boxes on the fracture surface of F1 indicate the size and location of the connected higher-magnification images.

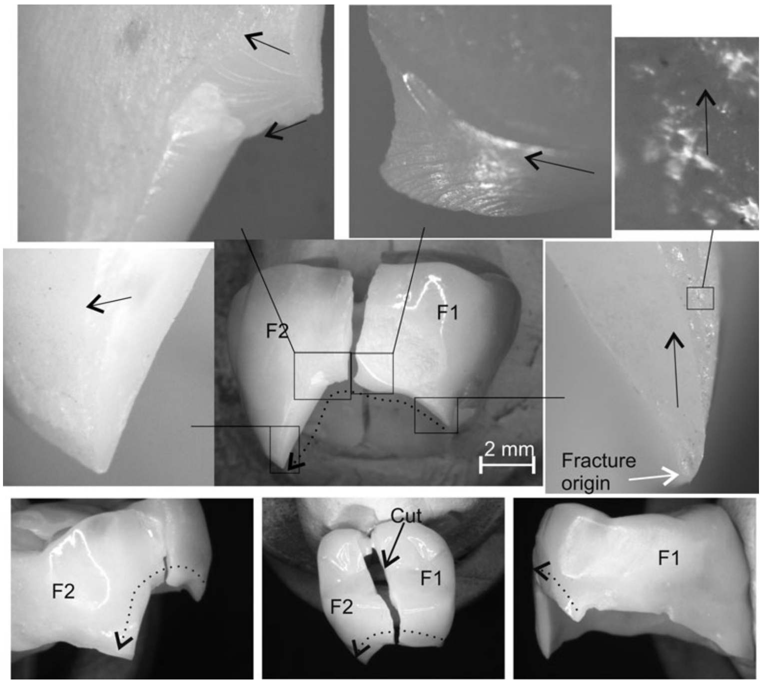

Fig. 5. Fractographic map of a zirconia crown with fracture of the palatal flange. The crown was cut in two across the occlusal surface for removal. The dotted lines indicate the direction of fracture, as indicated by the fractographic features seen in both core and veneer material. The black boxes on the central image indicate the size and location of the connected higher-magnification images.

secondary damage or in cases of veneer chipping in clinical fractures. The challenge has been to avoid contact damage in vitro. A recent in-vitro test on alumina crowns suggests that hoop forces cervically cause fractures that start in the cervical margin (22). In this study, contact damage from the loading device is avoided by distributing the axial load over a large part of the occlusal surface and the fracture modes are similar to clinical fractures (15).

Actual fracture rates are difficult to determine based on the present results. Only a limited number of dentists and dental technicians responded to our request for fractured specimens, so the proportions of samples are probably not representative of all fractures occurring. The reason why we did not receive more crowns with chipping damage is probably because the dentists did not know that they could send in an impression of these instead of the crown. In the period of collecting single-tooth ceramic restorations fractured during clinical use, we received 13 zirconia crowns, 14 glass-ceramic restorations, two restorations of unidentified material, and 27 alumina restorations (15). Glass-ceramic and alumina-based restorations have been used for several years and show an average annual fracture rate of 0.25 in clinical trials (3). The long time in clinical use may bias the reports of failure rates compared with the relatively new zirconia-based restorations (4–6, 41). There are very few clinical trials with single-unit zirconia restorations and these trials have a relatively short follow up (41–43). The retrieval of glass-ceramic crowns is more complicated than for the polycrystalline restorations, as a result of the adhesive fixation of remaining fragments, making it difficult to obtain them undamaged. Likewise, the removal of zirconia restorations with veneer fracture only, requires that the remaining crown is cut into two or more pieces for removal. It is likely that some fragments disappear and the area of importance for fractographic analyses may be destroyed in the process. This may explain why we did not receive many veneer fractures. Clinical trials with more restorations and a longer observation time are necessary to reliably assess the success rates of zirconia compared with other dental ceramics and metal ceramics.

All-ceramic restorations fracture in similar ways regardless of the composition of the core material. Core fractures of zirconia crowns seem to occur more often than expected. The fractographic analyses of retrieved restorations indicate that the weakest point of a single-tooth restoration is at the margin. The design of preparation and restoration seems to have an important impact on fracture rates and fracture modes. Further studies of clinically relevant fracture testing are necessary in order to suggest different strategies for design, handling, and tooth preparation.

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