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ORIGINAL ARTICLE

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

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Abstract

Objectives The aims of this study were set as follows:

1. To provide verifiable criteria to categorize the ceramic fractures into non-critical (i.e., amenable to polishing) or critical (i.e., in need of replacement)
2. To establish the corresponding survival rates for alumina and zirconia restorations
3. To establish the mechanism of fracture using fractography

Materials and methods Fifty-eight patients restored with 115 alumina-/zirconia-based crowns and 26 zirconia-based fixed dental prostheses (FDPs) were included. Ceramic fractures were classified into four types and further subclassified into "critical" or "non-critical." Kaplan–Meier survival estimates were calculated for "critical fractures only" and "all fractures." Intra-oral replicas were taken for fractographic analyses.

Results Kaplan–Meier survival estimates for "critical fractures only" and "all fractures" were respectively: Alumina single crowns: 90.9 and 68.3 % after 9.5 years (mean 5.71±2.6 years). Zirconia single crowns: 89.4 and 80.9 % after 6.3 years (mean 3.88±1.2 years). Zirconia FDPs: 68.6 % (critical fractures) and 24.6 % (all fractures) after 7.2 and 4.6 years respectively (FDP mean observation time 3.02±1.4 years). No core/framework fractures were detected.

Conclusions Survival estimates varied significantly depending on whether "all" fractures were considered as failures or only those deemed as "critical". For all restorations, fractographic analyses of failed veneering ceramics systematically demonstrated heavy occlusal wear at the failure origin. Therefore, the relief of local contact pressures on unsupported ceramic is recommended. Occlusal contacts on mesial or distal ridges should systematically be eliminated.

Clinical relevance A classification standard for ceramic fractures into four categories with subtypes "critical" and "non-critical" provides a differentiated view of the survival of ceramic restorations.

Keywords All-ceramic restoration · Zirconia · Alumina · Survival · Chipping · Fracture · Fractography

Introduction

Over the last years, chipping of veneering ceramics has been recognized as the most frequent technical complication of all-ceramic single crowns (SCs) [1, 2] and multiunit fixed dental prostheses (FDPs) [3–6]. Further, clinical studies indicated that fractures of the veneering ceramic were more frequent with zirconia frameworks than with conventional metal–ceramic restorations [4, 7].

For alumina-based SCs, a 5-year survival rate of 96.4 % (mean follow-up period 4.5 years) was found in a systematic review [8]. The estimated rate of crowns lost due to framework fractures ranged between 0.11 and 0.67 % (% crowns/year). A detailed account of the crowns lost due to fracture of the veneering ceramic was not provided. Comparable figures

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were published by Zitzmann et al. [9] (100 % survival for anterior restorations and 98.8 % for posterior restorations at 5 years), Kokubo et al. [10] (90.2 % at 5 years), and Sorrentino et al. [11] (95.2 % at 5 years). In the above studies, chippings of the veneering ceramic resulting in crown replacement ranged between 0 and 3 %, whereas fractures through the core occurred in 0–5 % of the restorations. Clinical data on zirconia-based SCs are scarce. In short-term studies, failure rates ranged from 0 to 11.2 % at 2–5 years [12–17]. However, the rates of "biological" and "other complications" were not specified relative to "fractures of the ceramic" [13, 17]. According to these studies, fractures of the veneer requiring replacement of the crowns were few and ranged between 0 and 1.9 % at 2–5 years. Only one fracture of the zirconia core was reported [12]. Current clinical studies on zirconia-based multiunit FDPs [18–21] confirm previous systematic reviews [4–6]: chipping of the veneering ceramic was a frequent complication, whereas fractures of the core only seldom occurred.

Problematically, an all-encompassing assessment of these studies is hampered by the lack of standardized definitions as to which type of fracture is to be considered a mere "complication" and which resulted in "failure" of the restoration. Regarding existing criteria, three evaluation systems have been extensively used. First is the U.S. Public Health Service (USPHS) or "Ryge" system [22]. In this classification, code "Delta" denoted restorations needing replacement, while "Alfa," "Bravo," and "Charlie" were either satisfactory or at least repairable. Second is the California Dental Association (CDA) ratings [23] which proposed criteria for "acceptable" and "unacceptable" restorations regarding "margin integrity," "anatomic form," and "color and surface." Third is the FDI system [24] with its classification into "clinically sufficient/satisfactory," "unsatisfactory but reparable," and "poor." Still, there are ambiguities in these systems which prevent an unequivocal interpretation of published survival estimates [4, 25] and therefore fail in delivering a clear message for the clinical decision-making process [25].

In a recent study [4], an attempt was made to address the problem by grading veneer chippings according to their severity and treatment modality. Small veneer flakes that could be polished qualified as "grade 1." Moderate veneer chippings that were repaired with composite qualified as "grade 2," and "grade 3" denoted severe chipping that required replacement of the restoration. Still, the criteria pertaining to each level of severity were not described in detail.

It thus appears that a detailed description of the morphology of the fractures specifying their extension and hence permitting a classification into "critical" vs. "non-critical" is needed. In the present acception, "critical" denotes failures in the form of fractures beyond repair. Conversely "non-critical" indicates fracture sites which can be either polished or restored using bonding techniques.

In light of the above, the aims of the present study were set as follows:

1. To establish the criteria for a classification of clinical fractures into non-critical (may be corrected by polishing, reshaping, or bonding) or critical (i.e., needing replacement)
2. To determine the survival estimates (critical only and all-fracture included) for alumina- and zirconia-based SCs and FDPs, for observation times of 3 to 9 years
3. To examine available broken fragments or sites regarding the mechanism of fracture

Materials and methods

Study design

The study had both a retrospective component and a prospective component. First, the records of all patients who had been restored with alumina- or zirconia-based restorations between January 2001 and December 2007 were retrieved. These patients were then asked to participate in the prospective part of the study. In January 2008, those who agreed were examined and the condition of their restorations was recorded. To increase the patient population, starting January 2008, more patients were recruited to the study. This latter group was followed for a minimum of 3 years. Both groups were recalled at yearly intervals for an assessment of their ceramic crowns and multiunit FDPs. The study was approved by the Ethics Committee of the University of Geneva (Ref. 11-060/Psy 11-006). Informed consent was obtained from all patients prior to their inclusion into the study.

Patients and restorations

For the retrospective–prospective part of the study (2001–2007), 29 patients were retrieved. They had been fitted with 73 crowns and 9 multiunit FDPs.

For the prospective part of the study (2008 onwards), another 29 patients (42 crowns, 17 multiunit FDPs) were recruited. The "prospective group" thus totaled 58 patients (33 women, 25 men) with a mean age of 51 years (range 24–79 years). These 58 patients had been restored with a total of 141 restorations of which 76 were tooth-retained and 65 were implant-supported. Among these, 19 were screw-retained (5 zirconia SCs, 14 multiunit FDPs) and 46 were cemented. Ninety-one restorations were cemented with resin-based cements (20 Compolute/EBS multi, 3M ESPE; 62 RelyX™ Unicem, 3M ESPE; 9 Panavia F2.0, Kuraray), 18 with glass ionomer (Ketac™ Cem, 3M ESPE), and 13 with temporary cement (Temp-Bond, Kerr). The occlusion was adjusted so that each tooth presented at least one stable occlusal contact in

Table 1 Total SC distribution

	Alumina	Zirconia
Anterior	26	11
Posterior	31	47
Total	57	58
Implant	8	36
Tooth	49	22
Total	57	58

SC single crown

maximum intercuspation. Contacts in lateral excursions on the restorations were eliminated. A Michigan-type bite splint was provided whenever heavy nocturnal bruxism was suspected.

Regarding the ceramic systems, 57 alumina-based crowns (NobelProcera Alumina™), 58 zirconia-based crowns (NobelProcera Zirconia™ (57); e.max® ZirCAD, Ivoclar (1)), and 26 zirconia-based multiunit FDPs (NobelProcera Zirconia™ (18); Zeno®, Wieland Dental GmbH (5); Lava, 3M Espe (1); DC-Zirkon, DCS Dentalsysteme GmbH (1); Cares®, Straumann (1)) were placed. The veneering ceramic for alumina and zirconia restorations was layered by hand. In all but three instances, Allux® (Wieland) and Zirox® (Wieland) were used. One zirconia SC was overpressed with e.max ZirPres® (Ivoclar), one multiunit FDP was veneered with Creation (Willi Geller International GmbH) and another with Lava Ceram (3M ESPE). An overview of the distribution of SCs and multiunit FDPs is provided in Tables 1 and 2.

Data collection

The "retrospective group" had been examined and documented at yearly intervals by faculty members. For these patients, the type of fracture (if any) and the date of occurrence were taken from the charts.

The prospective group was recalled once a year and examined by one single clinician (ODM). Besides, the patients were asked to inform the clinician of any events (chipping, fracture, or other matter of concern) occurring with their restorations between recall appointments.

Table 2 Total muFDP distribution

	3u	4u	5u	6u	Total
Anterior	2	6	1	3	12
Posterior	6	8	0	0	14
Total	8	14	1	3	26
Implant	7	12	1	1	21
Teeth	1	2	0	2	5
Total	8	14	1	3	26

FDP fixed dental prosthesis, *u* unit, *mu* multiunit

Clinical examination

During the oral examination, the ceramic surfaces were first air-dried and then scrutinized visually and with the aid of an explorer. In addition, the restorations were transilluminated with a 1500-mW/cm^2 polymerization lamp (Bluephase, Ivoclar-Vivadent) to detect cracks located within the veneering ceramic. Intra-oral photographs were taken with a digital camera. Occlusal contacts were located and marked with red or blue occlusion paper (Arti-Check, 40 μm, Bausch) and photographed. When chippings were detected, intra-oral replicas of the fracture sites were taken for microscopic evaluation [26]. Only fracture events were included into the statistical analysis. No failures of biological origin were observed in this study.

Clinical classification of fractures of ceramic restorations

The fractures were classified into four categories according to their severity. Type 1 and 2 fractures were further subdivided into "non-critical" (i.e., can be amended) and "critical" (i.e., the restoration must be replaced) (Table 3). A description of the criteria for each category follows.

Type 1: Crack in the veneer

Type 1a: Non-critical flaw inside the veneering ceramic (Fig. 1)

The crack is visible by transillumination or in specific light incidences only. The crack is subtle in appearance and has no effect on the appearance of the restoration. Such cracks may be stable or ultimately result in fracture.

Type 1b: Critical fissure in the veneering ceramic (Fig. 2)

Such cracks are clearly visible by the patient either as a change in color or due to overt staining of the fissure. Type 1b cracks represent an irremediable esthetic impairment.

Table 3 Clinical classification of ceramic fractures

Classification	Description of fracture	Critical/Non-critical
Type 1	Crack of the veneering ceramic	Non-critical (1a) Critical (1b)
Type 2	Chipping restricted to veneering ceramic	Non-critical (2a) Critical (2b)
Type 3	Chipping exposing the core	Critical
Type 4	Fracture of the core	Critical

Non-critical: Fractures, which can be corrected by polishing, reshaping, or bonding. They do not require replacement of the restoration. These defects do not compromise cosmetics and/or function. Critical: Fractures which require a replacement of the prosthesis

Fig. 1 Type 1a fracture: non-critical crack of the veneer. The crack is barely visible and of reduced extent

Fig. 2 Type 1b fracture: critical crack of the veneer. The crack was clearly visible due to a color staining after composite reparation. This fracture demands a replacement of the crown

Fig. 3 Type 2a fracture: non-critical chipping of the veneer. The chipping occurred in the form of a delamination of a palatal cusp. The site could be easily reshaped and polished; the opposing natural tooth had contact with other sites of the FDP, and therefore, the fracture was considered non-critical

Fig. 4 Type 2b fracture: critical chipping of the veneer showing an irremediable loss of morphology and esthetics. A new restoration must be fabricated

Fig. 5 Type 3 fracture: chipping of the veneer with core exposure. Due to the important loss in morphology and function, this multiunit FDP needed to be replaced

Fig. 6 Type 4 fracture: fracture of the core. An example of core fracture of an implant-supported screw-retained FDP. There were no core fractures in the present study

Type 2: Chipping of the veneer

Type 2a: Non-critical chipping (Fig. 3)

A chipping of the veneer is considered "non-critical" when the defect does not compromise the esthetics or the function of the restoration. The defect can be amended by reshaping, polishing, and/or bonding.

Type 2b: Critical chipping (Fig. 4)

A "critical" veneer fracture denotes an irretrievable loss of morphology. The impairment in cosmetics and/or function is such that a new restoration must be fabricated.

Type 3: Chipping of the veneering ceramic with core exposure (Fig. 5)

This type of fracture is critical by nature. It denotes a major loss in morphology and implies significant impairments in cosmetics and function. Such a restoration demands replacement.

Type 4: Fracture of the core (Fig. 6)

A fracture of the core is always considered critical.

If a single restoration presented two different types of fractures, only the highest category was recorded.

Fractographic analysis

Descriptive fractography is a semiquantitative tool that assists in characterizing the mechanism of fracture [27]. By using an in vivo replication technique [26] of the fractured surface and SEM analysis, it is possible to locate the origin (i.e., the starting point) of the crack and its direction of propagation [28]. These findings may then provide insights on the mechanism of the fracture. For a detailed explanation of fractographic procedures, see reference [28].

Table 4 Fractures of alumina crowns

	Tooth-supported	Implant-supported
Type 1a: non-critical crack	–	–
Type 1b: critical crack	1	–
Type 2a: non-critical chipping	8	–
Type 2b: critical chipping	3	–
Type 3: chipping with core exposure	–	–
Type 4: fracture of the core	–	–
Total fractures	12	–

Table 5 Fractures of zirconia crowns

	Tooth-supported	Implant-supported
Type 1a: non-critical crack	–	–
Type 1b: critical crack	–	–
Type 2a: non-critical chipping	1	3
Type 2b: critical chipping	–	2
Type 3: chipping with core exposure	1	1
Type 4: fracture of the core	–	–
Total fractures	2	6

Data analysis

The observation time was defined as the time span between the day of placement and the last follow-up appointment or the date of fracture. Due to the sample sizes available, single crowns and individual FDPs respectively were taken as the statistical units. Only fracture-related failures were considered for data analysis. All fractures leading to the replacement of the restorations were defined as "critical", and those that did not require replacement were considered "non-critical". No data were missing during the follow-up period. Kaplan–Meier survival estimates were calculated for "non-critical", "critical", and all fractures ("critical" and "non-critical"). The logrank differences between materials and types of abutments were also computed. The confidence level was set to 95 % ($p<0.05$). All analyses were performed using Stata intercooled 13.0 (STATA Corp., College Station, TX, USA).

Results

Fracture types and fractographic analyses

An illustrative overview of all fractures encountered on alumina- and zirconia-based single crowns as well as on multiunit FDPs is

Table 6 Fractures of zirconia FDPs

	Tooth-supported	Implant-supported
Type 1a: non-critical crack	–	–
Type 1b: critical crack	–	1
Type 2a: non-critical chipping	3	4
Type 2b: critical chipping	–	4
Type 3: critical chipping with core exposure	2	1
Type 4: fracture of the core	–	–
Total fractures	5	10

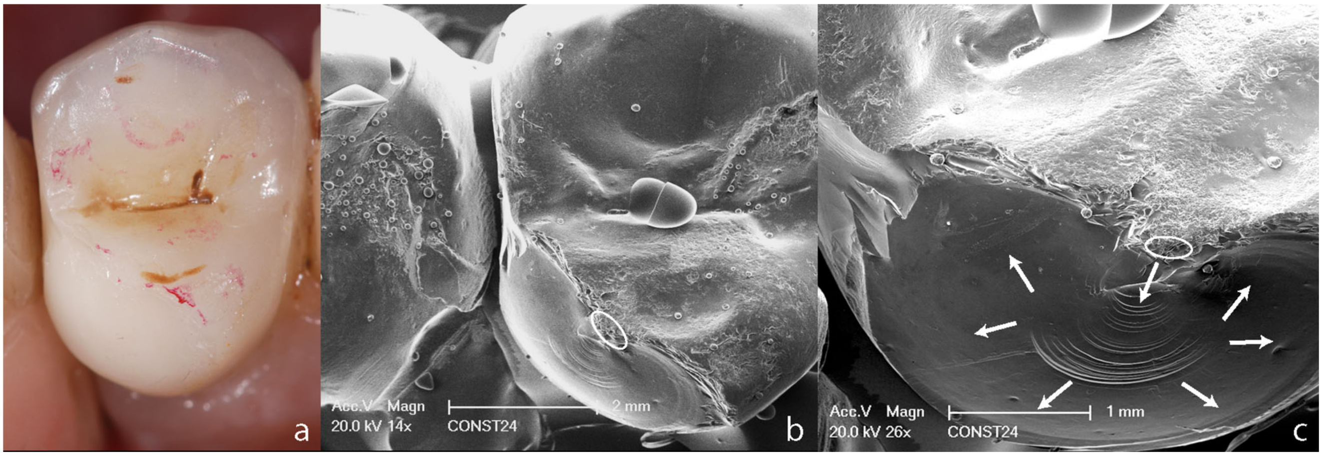

Fig. 7 **a**–**c** Fractography of a type 2a (i.e., non-critical) fracture. The crack leading to ultimate chipping started in a zone of occlusal wear (*white ellipse*: note roughness). It then proceeded in an apical direction inside the mesiopalatal surface until ultimate breakage (*arrows*)

provided in Tables 4, 5, and 6. An account of available fractographic views as related to fracture types follows.

Type 1 fractures: Crack in the veneer

By nature, type 1 flaws are not amenable to fractographic analyses.

Type 2 fractures: Chipping of the veneer

The fractographic analysis of a type 2a fracture is shown in Fig. 7a–c on an implant-supported multiunit FDP (Zeno framework, Zirox veneering ceramic). The palatal chip on the first upper premolar developed between the third and fourth recall appointment. SEM views revealed the origin of he fracture

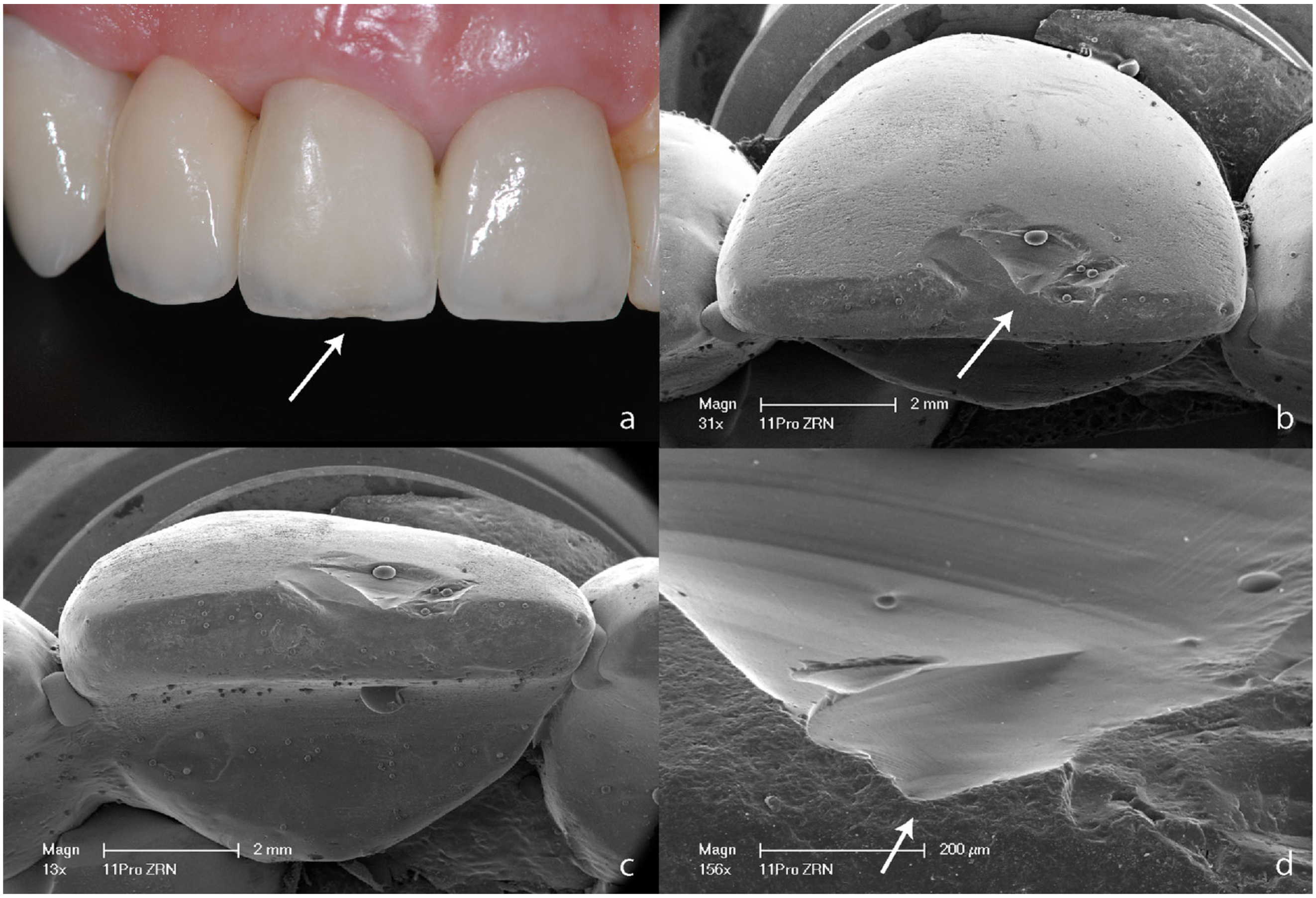

Fig. 8 **a**–**d** Fractography of a type 2a (i.e., non-critical) fracture. The crack leading to ultimate chipping started in a zone of incisal wear (*white arrows*: note roughness). The site was reshaped and polished

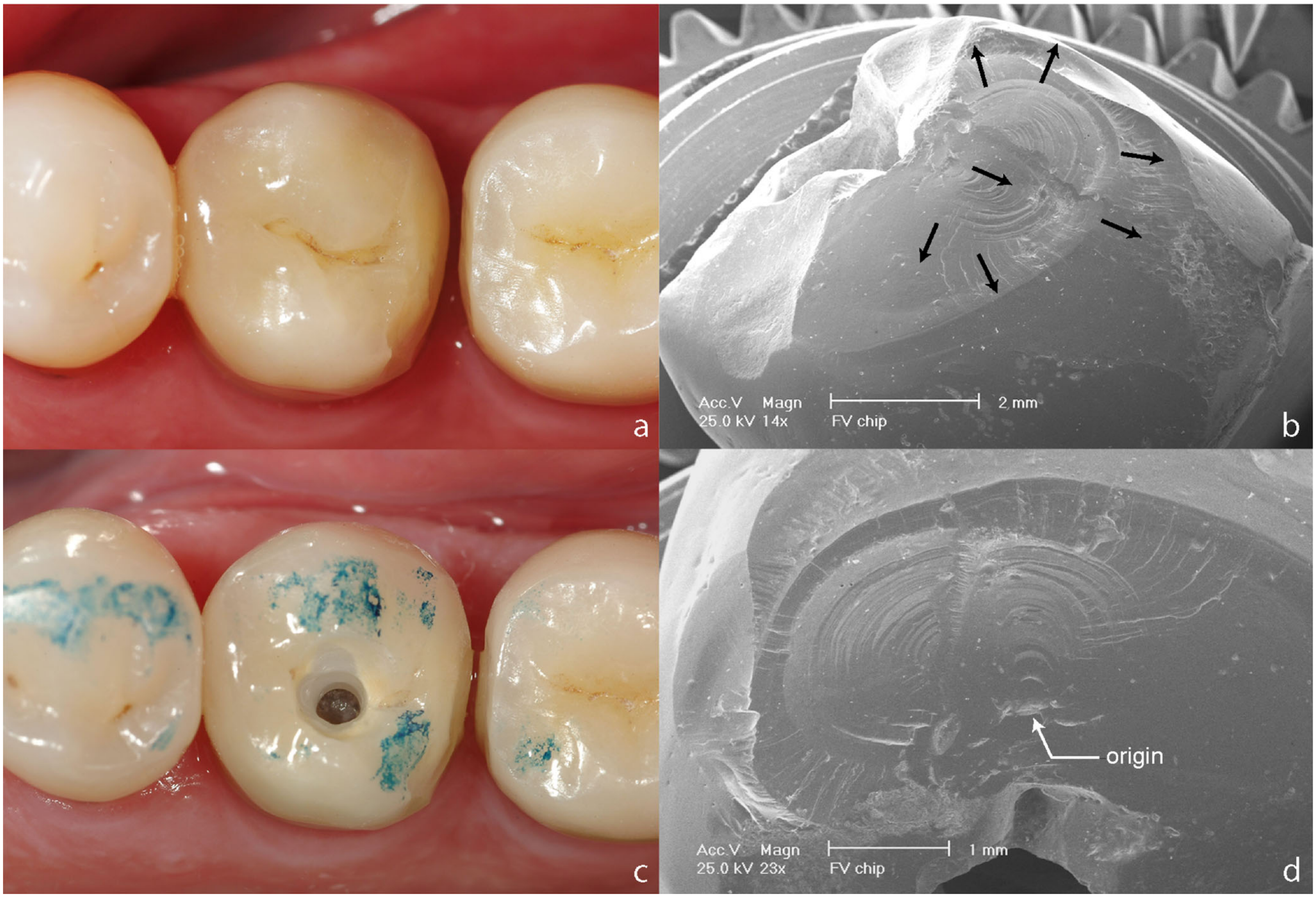

Fig. 9 a–d Fractography of a type 2b critical fracture. The veneering ceramic of a cement-retained implant crown fractured after 1.5 years resulting in the loss of the distal interproximal contact point. The occlusal contacts, although strong, were not linked to the failure origin

(white ellipses). Crack formation started in a zone of heavy occlusal wear (note the rough zone on the occlusal surface (Fig. 7b). The crack then propagated inside the mesiopalatal surface in an apical direction (white arrows). Observe the arrest/hackle lines on the surface of the ceramic. These lines concentrically radiate from the fracture origin (Fig. 7c). They are perpendicular to the direction of crack progression.

Another type 2a fracture is shown in Fig. 8a–d. The restoration was part of a tooth-borne maxillary multiunit FDP (Procera Zirconia framework, Zirox veneering ceramic). The small chip on the incisal edge appeared after 2 months. Here also, chipping started in a zone of roughness consecutive to occlusal wear (white arrows). The restoration then delaminated buccally (Fig. 8b–d).

A type 2b fracture is shown in Fig. 9 illustrating a zirconia single crown (Procera Zirconia framework, Zirox veneering ceramic) cemented on a screw-retained zirconia abutment. The veneering ceramic fractured after 1.5 years resulting in the loss of the distal interproximal contact point. To access the screw channel, the crown was perforated and the abutment–crown complex was removed. SEM fractographic analysis (Fig. 9b, d) revealed a failure origin located inside the veneering ceramic (Fig. 9d; white arrow). In this instance, the flaw that caused the ultimate failure was introduced during the fabrication of the restoration. During occlusal loading, stress concentrations appeared around the defect and induced the incipient crack. The crack then propagated radially and apically to eventually delaminate the entire distal surface.

Figure 10a, b also illustrates a type 2b fracture on a tooth-borne restoration on a lower premolar (Procera Alumina framework, Allux veneering ceramic). A major chip detached from the distolingual aspect of the restoration after 4 years, thereby causing a partial loss of the interproximal contact. This fracture was clearly caused by heavy occlusal function as indicated by the SEM views (Fig. 10c, d). Note the large zone of occlusal wear next to the formerly unsupported ceramic (Fig. 10d; black arrows). In this instance, the rubbing of antagonistic surfaces roughened the lower premolar's ceramic, thereby creating peaks and crevices in which stresses concentrated. Then, the forceful occlusal contact detached the distolingual fragment from the crown (Fig. 10c, d).

Another type 2b fracture is shown in Fig. 11. Multiple fractures occurred on a four-unit implant-supported FDP (Procera Zirconia framework, Zirox veneering ceramic) after 2 months (Fig. 11a; black arrow). The fracture originated at the occlusal surface next to an important zone of contact wear

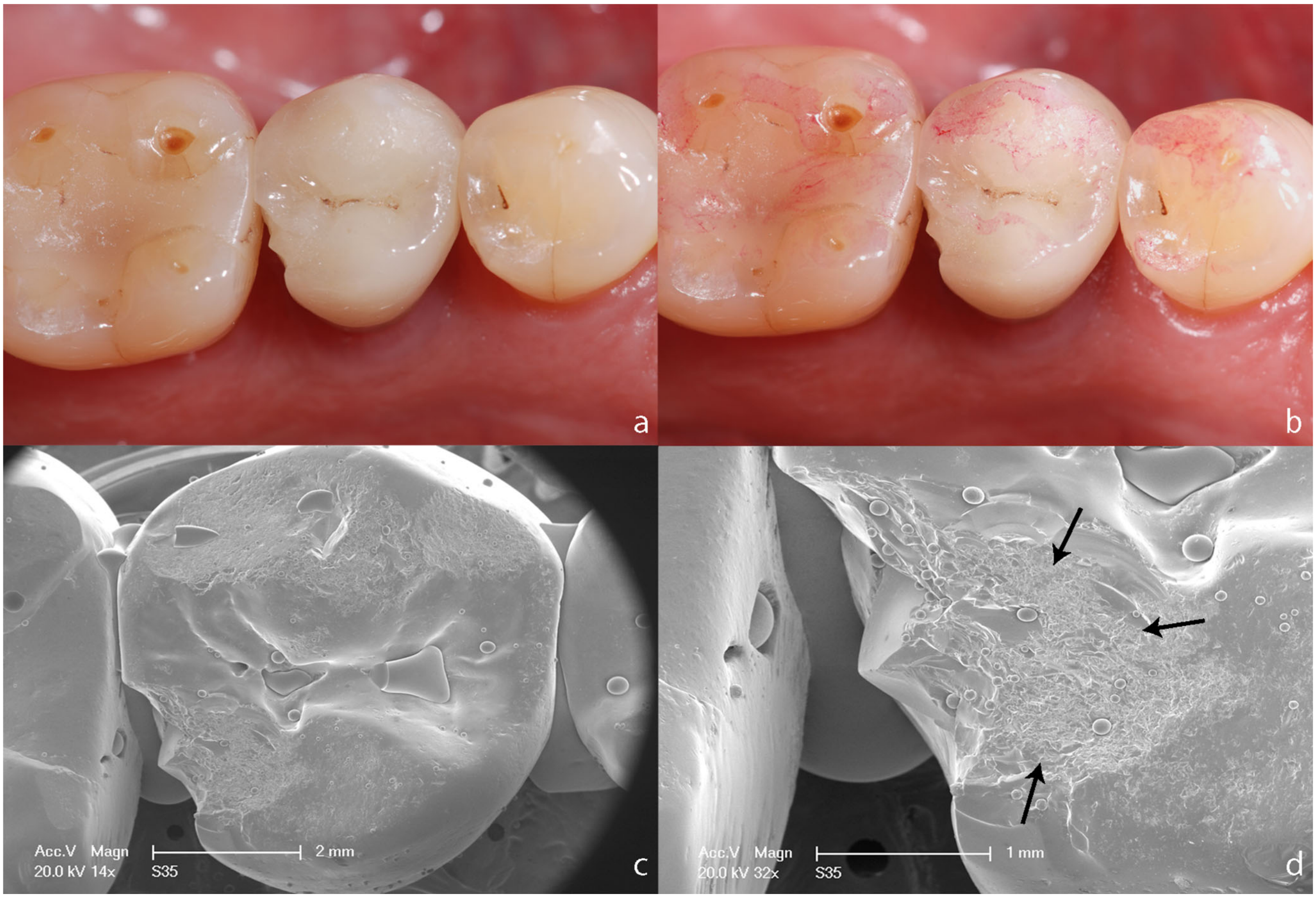

Fig. 10 **a**–**d** Fractography of a type 2b critical fracture after 4 years on a tooth-borne restoration. Here also, the SEM analysis showed localized occlusal wear (*black arrows*) next to the ceramic fracture. This chipping was clearly caused by excessive occlusal function

(Fig. 11b, c; black arrows). In addition to wear, SEM analysis also revealed defects in the veneer ceramic.

Type 3 fractures: Chipping with core exposure

Figure 12 illustrates a tooth-borne single crown (Procera Zirconia framework, Zirox veneering ceramic) that lasted 4 years. The SEM views demonstrated extensive wear and chippings of the occlusal surface which exposed the core in numerous locations (black arrows).

Type 4 fractures: Fracture of the core

There were no type 4 fractures is this study.

Fracture types and survival estimates

Alumina single crowns

Fifty-seven alumina-based SCs (26 anterior, 31 posterior, 8 implant-supported) were followed for a mean observation

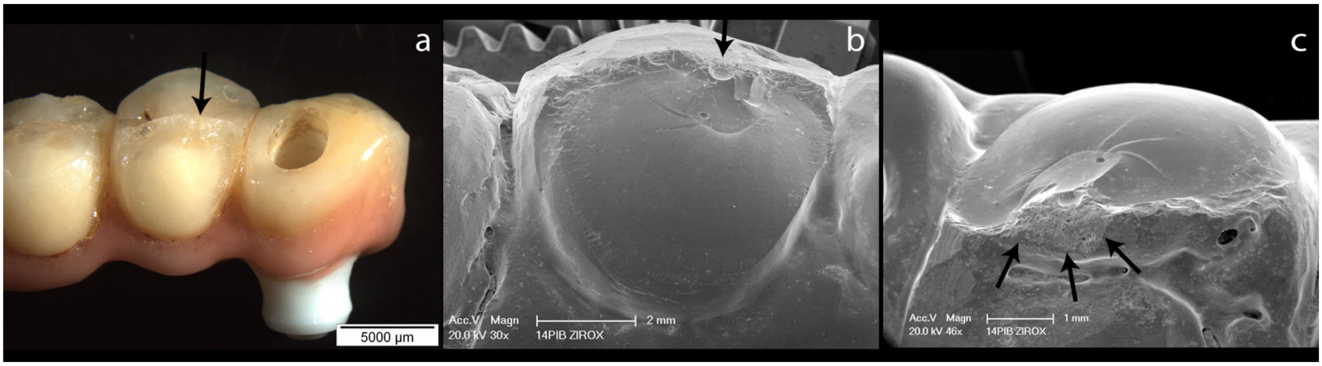

Fig. 11 **a-c** Fractography of a type 2b critical fracture after 2 months. The patient was a heavy bruxer. The fracture also originated at the occlusal surfaces

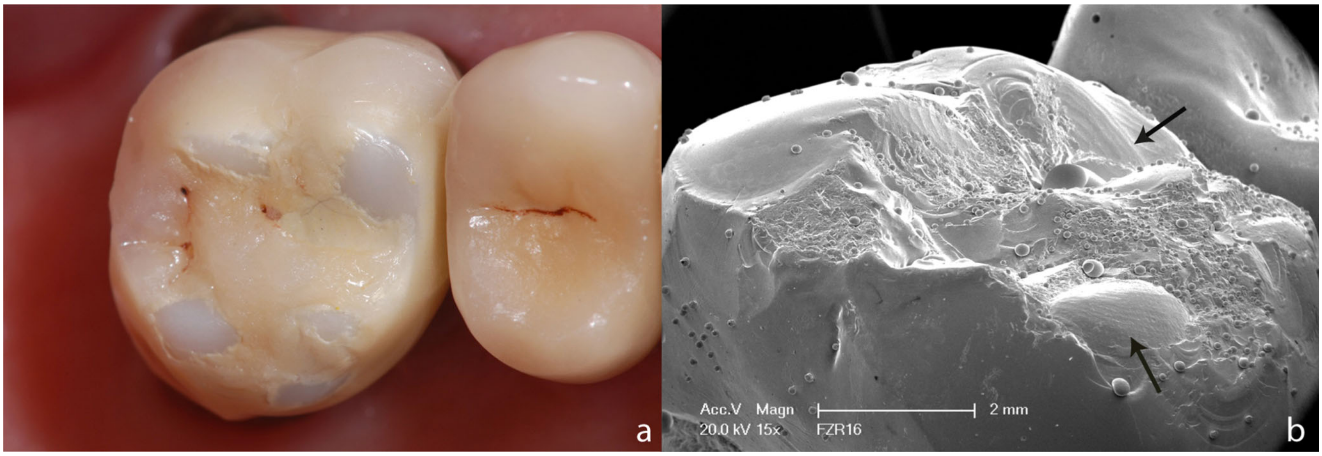

Fig. 12 **a**, **b** Fractography of a type 3 fracture after 4 years. The SEM analysis revealed an abraded occlusal surface with core exposure in several locations. The *black arrows* illustrate the machined surface of the exposed core

time of 5.71±2.6 years (range 1.4–9.5 years). Table 4 lists the fracture types observed. No core fracture occurred in alumina-based restorations. Eleven chippings and one crack were detected (21 % of the sample). Four fractures were deemed "critical" (i.e., types 1b, 2b; 7 %) and eight were "non-critical" (i.e., type 2a; 14 %). The Kaplan–Meier survival estimate for "all" fractures was 68.3 % at 9.5 years. When only "critical" fractures were considered, the survival estimate at 9.5 years was 90.9 %. Figure 13 presents the Kaplan–Meier survival plots up to 9.5 years. Note the cascade of "non-critical" events that occurred between the fourth and the fifth year.

Zirconia single crowns

There were 58 zirconia SCs (11 anterior, 47 posterior, 36 implant-supported) which were followed for a period of 3.88±1.2 years (range 0.21–6.3 years). The fracture types are presented in Table 5. No core fracture was observed in zirconia-based SCs. Eight chipping fractures (14 % of the sample) occurred of which four were critical (type 2b–type 3; 7 %) and four were non-critical (type 2a; 7 %). The Kaplan–Meier survival estimate for all fractures was 80.9 % at 6.3 years. The survival estimate for critical fractures was 89.4 % (Fig. 14).

Zirconia multiunit FDPs

Eleven patients fitted with 26 zirconia FDPs (3 or more units each) were followed for a mean time of 3.02±1.4 years (range 0.03–7.2 years). Twelve FDPs (9 patients) were located in anterior sites and 14 (9 patients) in the posterior zone. Twenty-one were implant-supported and 5 were tooth-borne. The majority of the restorations comprised 3 or 4 units. Three

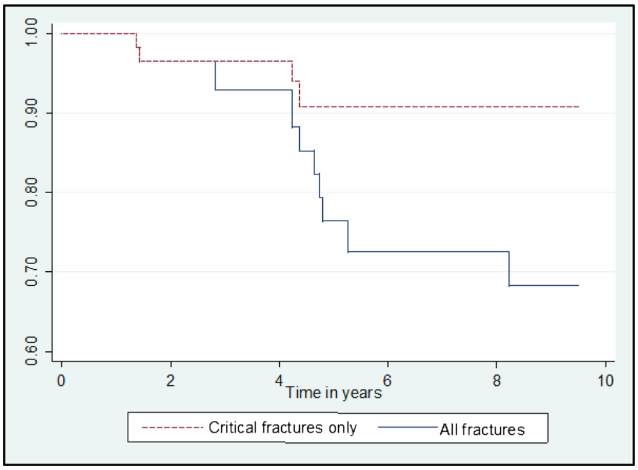

Fig. 13 Kaplan–Meier product limit survival estimates of alumina crowns for an observation time of 9.5 years (mean 5.71 years). The survival estimate for "critical" fractures at 9.5 years was 90.9 % (*red line*). The survival estimate for all fractures at 9.5 years was 68.3 % (*blue line*)

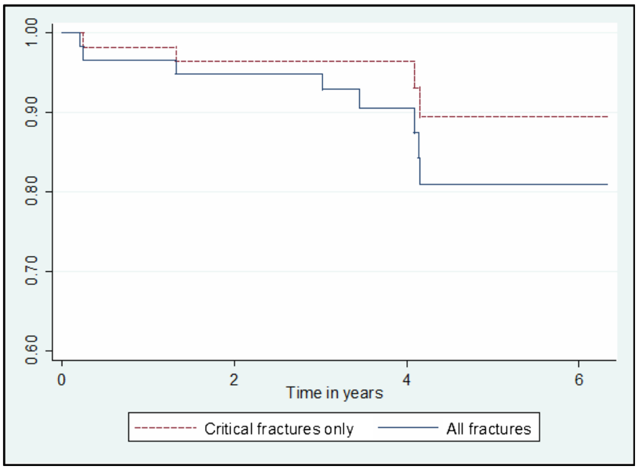

Fig. 14 Kaplan–Meier product limit survival estimates of zirconia crowns for an observation time of 6.3 years (mean 3.88 years). The survival estimate for critical fractures was 89.4 % at 6.3 years (*red line*). For all fractures, the survival estimate was 80.9 % (*blue line*)

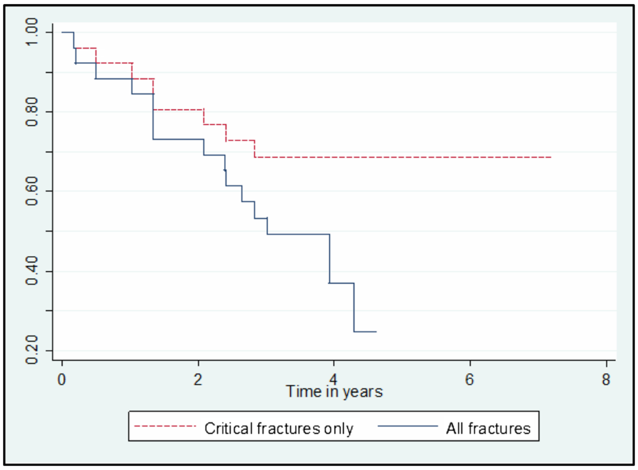

Fig. 15 Kaplan–Meier survival estimates of zirconia multiunit FDPs for an observation time of 7.2 years (mean 3.02 years). The survival estimate curve for critical fractures was 68.6 % at 7.2 years (*red line*). The survival estimate for all fractures was 24.6 % at 4.6 years (*blue line*)

types of veneering ceramics were used on five different zirconia framework materials. For the 26 FDPs (103 units) "critical" fractures of the veneering ceramic were observed in 8 FDPs (types 1b, 2b, 3; 30.7 % of the sample) (Table 6, Fig. 15), resulting in a survival estimate of 68.6 % at 7.2 years. Six (23 %) were implant-supported and two (8 %) were tooth-borne. When considering all fractures (15 events; 57 % of the sample), a survival estimate of 24.6 % was obtained after 4.6 years. Logrank tests indicated that the incidence of fractures was not dependent on the type of abutment (i.e., tooth or implant; logrank test 0.29, p=0.59).

Effect of material (Al_2O_3 vs. ZrO_2), sex, abutment, and cement type

The number of "critical" fractures was the same for both materials (logrank test 0.10, p=0.75). As for non-critical fractures, although more fractures occurred in alumina-based crowns, no statistically significant difference was found between the two materials (logrank test=0.00, p=0.99).

The fracture event was not associated with sex (logrank test 0.30, p=0.59), type of abutment (logrank test 0.06, p=0.80), or cement type (logrank test 1.82, p=0.61).

Effect of anterior vs. posterior restorations

Logrank tests showed that "critical" and "all" fracture events were not associated with anterior or posterior alumina-based crowns (logrank test 0.11, p=0.74; logrank test 0.02, p=0.89), zirconia-based crowns (logrank test 0.82, p=0.36; logrank test 0.02, p=0.89), or zirconia multiunit FDPs, respectively (logrank test 1.22, p=0.27; logrank test 2.01, p=0.15).

Discussion

Survival estimates

This retrospective–prospective study on the complication rate of alumina- and zirconia-based single- and multiple-unit restorations provided a differentiated view on "survival," "breakage," and "failure" as the fracture events were categorized according to their severity (types 1–4) and clinical implication, that is, "non-critical" (repairable by reshaping and polishing) and "critical" (i.e., needing replacement). Self-evidently, the survival estimates varied considerably when every minor chip was entered into the Kaplan–Maier statistic as "failure" or when only the critical fractures, that is, those needing crown replacement, were included into the analysis. For alumina SCs, for instance, the difference amounted to 20 % as the survival estimate for "critical fractures only" was 90.9 % at 9.5 years—a rate which fell to 68.3 % when all "non-critical" chippings of the veneering ceramic were included. The same figures for zirconia SCs were 89.4 % at 6.3 years for "critical fractures only" with a decrease to 80.9 % for all fractures. In our population, zirconia-based multiunit FDPs were more prone to critical fractures as the survival estimate was 68.6 % for critical fractures only at 7.2 years which fell to 24.6 % when all ceramic fractures were included.

Still, in the present population, the amount of critical failures was high. One explanation is the inclusion of patients with signs of bruxism who are often excluded from clinical studies [29, 30]. Typically, these patients severely abraded their occlusal surfaces and provoked critical ceramic fractures with exposures of the zirconia cores. This observation is consistent with the data from a recent study on 23 patients with 31 zirconia multiunit FDPs [31]. Of the nine patients with signs of bruxism, two patients experienced fractures of the core of their restorations and six chipped the veneering porcelain after semi-permanent cementation, resulting in a 100 % chipping rate at 3.3 years [31].

From the 8 critically fractured multiunit FDPs, 6 (75 %) were implant-supported. Two of these were placed into a patient later identified as a bruxer, one failed due to a flaw introduced during fabrication of the restoration, and three were large (i.e., full arch) multiunit restorations. In the pilot study on implant-supported full-arch zirconia FDPs conducted by Larsson et al. [32], fractures of the veneering ceramic occurred in 36 out of 89 units (40 %). After a follow-up of 8 years, 8 out of 9 patients presented fractures. The 9 original FDPs, though, were still in use. Indeed, as yet, an assessment of the risk of complete failure has not been reported for implant-supported restorations [32, 33]. A retrospective study of zirconia-based screw-retained prostheses supported by implants and including 65 SCs and 91 FDPs was recently made available [34]. The cumulative survival rate was 90.5 % after 5 years. Four fractures of the core (1 SC, 3 FDPs) and 5 critical chippings (3 SCs, 2 FDPs) were recorded.

In the present study, no core fractures were observed on SC restorations. These results are in agreement with previous studies that included alumina-based [35] and zirconia-based [14, 16, 17] single crowns. Still, fractures of alumina cores for single-unit restorations have been reported in a number of other clinical studies [1, 9, 10, 36, 37].

For FDPs, no core fractures were detected. This confirmed previous findings with low or non-existent fractures of the zirconia core itself [4–6]. No relation was established between the type of abutment and the type of fracture. The present sample size, however, is comparatively small and heterogeneous in its distributions. Larger sample sizes might have evidenced significant relationships.

Fractographic analyses

With minor exceptions, the SEM fractographies of the occlusal surfaces systematically demonstrated zones of roughness next to the origin of the fracture. More than likely, these zones were subjected to high pressures and excessive contact wear. Problematically, this phenomenon does not leave a finely polished surface but results in localized areas of overt roughness. This roughness, in turn, is conducive to stress concentrations at the bottom of the notches and crevices from which several cracks will start under the repeated impact of the occlusion. These cracks will then coalesce to a single fissure which progresses through the ceramic and leads to the ultimate fracture.

This relationship between roughness and incipient cracking was already noted in previous publications. Signs of wear from contact loading and arrest lines near the origin of the chipping were demonstrated [27, 28]. These clinical observations translate in vitro as the step-by-step cumulative damage in zirconia restorations under long-term cyclic loading [38]. In the latter (laboratory) study, at first, signs of wear and abrasion were detected. They were followed by an initial crack that formed below the loading area. Utilizing the multiple arrest line as indicators, the propagation of the fissure in a cervical direction was inferred. When intact specimens were sectioned and analyzed, three additional types of cracks demonstrated how the fracture front proceeded below the loading point starting from the established surface and subsurface damage [38].

The failure modes and reliability of 32 implant-supported three-unit zirconia FDPs (Procera, Nobel Biocare, Gothenburg, Sweden) veneered either by overpressing (NobelRondo Press) or by hand stratification (NobelRondo) were compared by Baldassarri et al. [39]. Both groups presented chipping of the veneering ceramic at the occlusal surface as the dominant complication. Still, chipping occurred at lower loads and at fewer cycles for overpressed FDPs. Fractographic analysis of the chipped areas indicated that cracks developed from the zone of contact in a buccoapical direction. Intermediate arrest lines were also noted [39]. In addition to the buccal chipping, fracture of the pontic in the contact area and through one of the connectors was observed in hand-veneered FDPs. This type of failure mode was also reported previously on three-unit zirconia FDPs [40].

Occlusal contact locations and framework design

The present findings have significant implications on the clinical location of occlusal contacts. The loss of the interproximal aspect of a restoration due to fracture of the ceramic can largely be prevented by systematically eliminating all occlusal contacts on mesial and distal ridges. The veneering ceramic in these areas is typically left unsupported by the stronger ceramic core and is therefore likely to fracture even under normal occlusal loads. When an interproximal wall is lost, the restoration must be replaced as food will be trapped between both teeth. Due to the large shearing forces, no lasting repair with adhesive composite resin is possible. In addition, the clinician should monitor the location of occlusal contacts over time. Relieving contacts on the margins and polishing visible zones of wear are advised. These particularly apply to multiunit FDPs for which the survival estimate was of 68.6 % only after 3 years due to wear-associated critical veneer chippings.

The core should be so designed as to provide firm support to the veneering material. Thick alumina or zirconia frameworks are to be favored to optimize the support of the veneering ceramic. Whenever the thickness of the veneer is twice or more than that of the core, the risk of chipping is increased considerably [4, 41, 42]. In response, so-called anatomical core designs have been used in clinical studies with promising results [43, 44]. To decrease the incidence of fractures of the veneering ceramic, Beuer et al. [45] demonstrated that an overpressing technique on anatomical zirconia frameworks may be a workable approach. Developing veneering ceramics of higher strength and fracture toughness is certainly desirable to reduce the incidence of chippings, but still, at present, only adaptations in the design of the supporting substructure will effectively reduce the number of fractures [41].

Assessing the severity of fractures

There is growing evidence that the incidence of chipping increases on full-ceramic restorations, which in turn has raised the question as to which criteria should determine the "success" or the "failure" of an all-ceramic restoration [25]. Terminologies such as "minor–major" chipping [46–48] and "technical complications" [3, 49] have blurred the issue as to how the severity of a fracture should be quantified. Noteworthy, in their systematic review, Heintze et al. [4] attempted to solve the problem by grading veneer chippings from 1 to 3 according to their severity and treatment options. Problematically, the authors did not list the clinical criteria that corresponded to each degree of severity [25]. Moreover, the authors concluded that a better description of the type of veneer fractures or material failures was needed based on the size and location of the breakage. In a recent systematic review of all-ceramic crowns [50], the fractures were categorized into “veneer chipping,” “veneer fracture,” and “core fracture combined with veneer breakage.” However, a clear gradation regarding the severity of the fractures was not provided.

In the present study, a new classification of the types of clinical ceramic fractures was proposed (types 1–4). It establishes a distinction between cracks (i.e., fissures) in the veneering ceramic without detachment, chipping with or without exposure of the core material, and fractures through the core ceramic. It also establishes the concept of “non-critical” implying a recovery by a mere reshaping/polishing of the fractured surface vs. “critical” in which the replacement of the restoration is required. These categories are intended to provide a finer tool for the analysis of survival studies.

Future studies might involve monolithic restorations. In these instances, the authors suggest to use types 1 and 2 (and their subclasses “critical” and “non-critical”) of the present classification for ceramic fractures.

Conclusions

Within the limitations of this study, the following conclusions are drawn:

- Classifying ceramic fractures into four categories with subtypes “non-critical” and “critical” permits a differentiated view of the survival data for single crowns and FDPs.
- Critical ceramic chipping and survival estimates of alumina- and zirconia-based single crowns are similar, that is, 90.9 and 89.4 % respectively.
- Zirconia multiunit FDPs were more prone to fractures of their veneering ceramic (survival estimate of 68.6 % at 7.2 years).
- The origin of fractures is typically associated with excessive occlusal wear. Therefore, the relief of local contact pressures on unsupported ceramic is recommended. Occlusal contacts on mesial or distal ridges should systematically be eliminated.

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Conflict of interest The authors declare no conflict of interest.

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