Clinical Behavior of Second-Generation Zirconia Monolithic Posterior Restorations: Two-year Results of a Prospective Study with *Ex Vivo* Analyses including Patients with Bruxism Clinical Signs

Short title: Clinical Behavior of Zirconia Monolithic Restorations

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Keywords: dental prosthesis, zirconia, computer-aided design/computer-aided manufacturing, wear

Abstract

Objectives: This study aimed to investigate (1) clinical outcomes of second-generation zirconia restorations, including patients with bruxism clinical signs, and (2) the material wear process.

Methods: A total of 95 posterior monolithic zirconia tooth-elements in 45 patients were evaluated, 85 on implants and 10 on natural teeth, and 20.3% of restorations being fixed partial dentures (FPDs). Occlusal contact point areas were determined and half of those areas were left unglazed and just polished. Restorations were clinically evaluated following criteria of the World Dental Federation and antagonistic teeth were examined at each evaluation time.

Wear *ex vivo* analyses using SEM and 3D laser profilometry were performed at baseline and after 6 months, 1 year, and 2 years respectively, temporarily removing the prostheses.
Results: The Kaplan-Meier survival rate of restorations was 93.3% (100% for FPDs) and the success rate was 81.8%, with 4 abutment debondings, 3 tooth-supported crown debondings (provisional cement use), 1 restoration fracture, 1 minor chipping, 1 core fracture, 1 root fracture, and 2 implant losses. 80% of catastrophic failures occurred in patients with clinical signs of bruxism (61.7% of patients). Complications were also observed on antagonistic teeth (3 catastrophic failures). Clinical evaluation of the restorations showed good results from the aesthetic, functional, and biological perspective. Zirconia wear was inferior to 15 μm, while glaze wear was observed on all occlusal contact areas after 1 year.
Conclusions: Monolithic zirconia FPDs are promising but the failure rate of single-unit restorations was not as high as expected in this sample including patients with bruxism clinical signs.
Clinical significance: Within study limitations, FPDs showed excellent short-term results but further research is needed for single-unit restorations considering samples, which do not exclude bruxers. The weak link is the restoration support or the antagonist tooth, one hypothesis being that zirconia stiffness and lack of resilience do not promote occlusal stress damping.

Keywords: dental prosthesis, zirconia, computer-aided design/computer-aided manufacturing, wear

1. Introduction

Three mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) was introduced in prosthodontics in the early 2000s as an alternative to metal due to its high strength and biocompatibility combined with a white appearance. 3Y-TZP has original properties since it is in a metastable state at room temperature and can transform from a tetragonal to a monoclinic (t-m) crystalline form under the effect of stress, giving zirconia high toughness in comparison with other ceramic materials. However, this transformation can also occur in a very slow process when the material is in contact with water: this aging phenomenon, called low-temperature degradation (LTD), can engender material surface alterations and fracture [1]. The first clinical reports about veneered zirconia-based crowns and fixed partial dentures have indicated a high rate of short-term failures due to a high rate of cohesive fracture of the veneering ceramic (chipping), which constitutes the weak link of the restoration [2–6]. This problem was confirmed with long-term studies [7-9].

Even if some recommendations have been formulated to reduce this problem, monolithic zirconia restorations have recently been introduced to avoid chipping and reduce fabrication costs [10]. However, this required the development of new zirconia materials with high-translucency properties. At present, there is a wide range of zirconia materials on the market in terms of composition and microstructure, and consequently properties.

Currently, three generations of zirconia materials are described [11]. First-generation zirconia is the original (3Y-TZP), which is used to produce frameworks for veneered restorations. The main characteristics of this generation are the low content in the cubic phase (<15%), the resulting high strength (1200 MPa) and toughness and a high opacity and refractive index. To improve translucency, the alumina content was reduced and/or the sintering temperature was increased to reduce porosities while increasing the grain size [12], introducing the second generation [11]. The aesthetic properties improvement allows for the fabrication of posterior monolithic restorations but changes in material composition and microstructure challenge resistance to LTD due to a higher metastability [12–14]. Aesthetic anterior monolithic restorations are now accessible using third-generation zirconia, which is even more translucent while resistant to LTD due to a higher cubic phase content (partially stabilized zirconia 4 mol% or 5 mol%: 4-YPSZ contains more than 25% of the cubic phase and 5-YPSZ more than 50%). However, the resulting mechanical properties are lower than the two previous generations (<700 MPa flexural strength for 5-YPSZ), since the cubic phase does not undergo stress-induced transformation.

Most publications reporting clinical outcomes with zirconia monolithic prostheses described restorations made from second-generation zirconia [15–28]. However, patients presenting high occlusal stress, such as those with bruxism, were included in only one study [28], which engenders important bias. Indeed, bruxism is reported to have a high prevalence [29], while manufacturers often recommend monolithic zirconia restorations for this indication.

Finally, material and antagonistic tooth wear was also a concern when zirconia monolithic restorations were introduced. Publications reporting *ex vivo* quantitative measurements of wear showed negligible wear of zirconia surfaces [20] and less abrasive effects on antagonist teeth than other ceramic materials; both polishing and glazing as finishing procedures were investigated [20,24,27,30]. Nevertheless, those measurements were performed on replicas, which was shown to engender significant imprecision in wear evaluation and counteracted SEM observations [31].

Consequently, an original prospective clinical study protocol that includes *ex vivo* analyses of the restoration was designed [32] to investigate (1) in-mouth LTD process of second-generation zirconia restorations on teeth and implants (2) biological, functional, and aesthetic clinical outcomes in patients with and without clinical signs of bruxism and (3) material wear. The present work reports the 2-year results related to clinical outcomes and wear analysis.

2. Materials and methods

2.1. Study design

The protocol of this prospective study was approved by the Ethics Committee of the University Hospital Center (CHU) of Liege and was registered on the ClinicalTrials.gov database (Identifier NCT02150226). The complete study design and protocol were previously published in detail [32]. The determination of the sample size was based on the LTD outcome. Written patient consent was obtained before inclusion and 47 patients were included from February 2014 to December 2015. The patients were treated by four experienced operators from the Department of Fixed Prosthodontics, Institute of Dentistry, CHU of Liege, Belgium. The eligibility criteria were the need for molar or premolar crowns (maximum 6 elements per patient). Restorations were realized either on teeth or implants and multi-unit restorations were also included, provided they were on implants and were limited to 3 elements (maximum 2 fixed partial dentures (FPDs) per patient). The exclusion criteria were severe or acute periodontal or carious diseases and poor oral hygiene. Patients with removable prosthesis as an antagonist were excluded. The participants received no financial compensation, although treatment and prostheses were free of charge.

2.2. Occlusal risk factors

The presence of bruxism was evaluated through clinical examination and self-reporting [33]. The presence of bruxism was recorded if the patient fulfilled at least two criteria: (1) reporting teeth grinding during the night or day and (2) the presence of at least one clinical sign among the following: abnormal attrition wearing facets on teeth, transitory pain or fatigue on waking felt in the jaw muscles, temporal headaches on waking, or jaw locking on waking related to teeth grinding during sleep [34].
Occlusal relationships were characterized as favorable or unfavorable based on the clinical examination. Class III or class II.2 malocclusion, anterior or posterior crossbite, edge to edge or open bite were considered as unfavorable occlusal relationships. The use of an occlusal nightguard was noted.

2.3. Clinical procedure and fabrication of the restorations

All of the clinical and technical procedures were performed in strict agreement with the clinical and technical instruction protocol validated by the ethics committee and following the manufacturers' recommendations. Teeth were prepared following standardized criteria (1.0 to 1.5 mm occlusal depth cut to achieve the appropriate occlusal anatomy, 1.0 to 1.5 mm functional cusp tip reduction, 0.5 mm gingival chamfer reduction, and a 6-8 degree taper to the axial walls). A double-mix impression was performed with high- and a low-viscous A-silicone impression material (Aquasil Heavy/XLV, Dentsply De Trey, Konstanz, Germany) and the same impression procedure was used for implant restorations. Two implant systems (NobelReplace, Nobel Biocare, Gothenburg, Sweden; and Standard Implants, Straumann, Basel, Switzerland) were used in this clinical study. Shade was registered with the Vita Classic System (Vita Zahnfabrik, Bad Säckingen, Germany). Restorations on antagonistic teeth were replaced in the presence of a deficient marginal joint, decay, or unadapted morphology.

CAD-CAM composite provisional crowns (Lava Ultimate, 3M, Seefeld, Germany) or PMMA provisional FPDs were designed with specific buccal and palatal grips to facilitate cemented crown removal [32]. Provisional restorations were in-mouth adapted, particularly regarding occlusal adjustments, and used as a model for the design of the zirconia restorations (Lava Plus, 3M, Seefeld, Germany). Lava Plus High Translucency Zirconia is a tetragonal polycrystalline zirconia partially stabilized with 3mol% Yttria engineered for high translucency and utmost strength. It has a lower Alumina content of 0.1% compared to Lava Frame Zirconia, optimally distributed within the material for maintaining aging stability. Sintering was performed following the manufacturer's instructions at 1450°C for 2 h. The zirconia restorations were tried in and if needed occlusal contact points were adjusted and polished. Firing of the glaze (IPS Empress stains and e.max Ceram Glaze, Ivoclar Vivadent, Schaan, Liechtenstein) at 780°C for 1 min completed the manufacturing process. Bonding to titanium abutments (1000er-Serie, Medentika, Hugelsheim, Germany) was performed with a resin composite cement, either RelyX Ultimate (3M, Seefeld, Germany) in the first part of the study, or Multilink Hybrid Abutment (Ivoclar Vivadent, Schaan, Liechtenstein) in the second part, following the manufacturers' recommendations, that is, after sandblasting the abutment and the zirconia restoration with 50 µm alumina particles.

The occlusal surface contact areas, which were not glazed, were randomly determined (Figure

1a). Four occlusal contact points (one contact per cusp) were determined on the molars and two on the premolars (Figure 1b). For molars, two cusps were randomly selected to remain unglazed: one centric cusp (unglazed centric cusp, UCC) and one non-centric (unglazed non-centric cusp, UNCC). The two other cusps were called the glazed centric cusp (GCC) and glazed non-centric cusp (GNCC). For premolars, one cusp was randomly selected to remain unglazed. Control areas were the buccal face (glazed) and the lingual/palatal face (unglazed) of the restoration.

Baseline analyses were performed before placement (see Section 2.4). Cemented restorations were sealed with eugenol-free cement (RelyX Temp NE, 3M), while screw-retained restorations were torqued at 35 Ncm^{-1}. Clinical evaluation was performed one week after placement (see Section 2.3). After 6 months, the restorations were clinically evaluated and then removed for *ex vivo* analyses. Provisional restorations replaced zirconia restorations during *ex vivo* analyses. After these analyses, zirconia restorations were placed again in the mouth of the patient. The same procedure was repeated after 1 and 2 years. All of the data were recorded in a specifically designed online database, so that clinical data, pictures, and *ex vivo* measurements could be easily available for consultation. The database is hosted on the university hospital secured server.

2.4. Clinical outcomes

2.4.1. Restoration evaluation

Clinical evaluation followed World Dental Federation recommendations and used World Dental Federation Instruments for assessing dental restorations [35]. This instrument is comprised of three dimensions (18 items): biological (six items), functional (seven items), and aesthetic (five items). The two items related to wear were not considered since the quantification was performed *ex vivo*, so only 16 items were reported in the study. Each item was assessed by clinical examination on a 5-point Likert scale (1 corresponding to a perfect restoration and 5 corresponding to a restoration that needs to be replaced). Two independent evaluators performed the evaluations after training on the e-calib web-based software and group training sessions. The type of support (tooth or implant) was registered. In addition to radiographs, pictures were taken of the restorations and the antagonistic teeth with the occlusal contact point registering.

2.4.2. Antagonistic teeth evaluation

The nature of the antagonistic teeth was registered at baseline. All of the complications and interventions were recorded.

2.4.3. Patient satisfaction level

The FDI evaluation included patient self-reported satisfaction, on a 5-point Likert scale, regarding the aesthetic appearance of the crown and/or function. Therefore, the criterion was divided into two sub-scores [35].

2.5. *Ex vivo* analyses

2.5.1. SEM observations

The removed crowns were observed with an JSM-6400 scanning electron microscope (JEOL Limited, Tokyo, Japan) to monitor the wear and glaze coating evolution.

2.5.2. Profilometry

For zirconia wear quantification, the restorations were scanned *ex vivo* with a custom-made device including an XY motorized board stage and a 100 nm resolution laser sensor (Keyence LK G30 with LK GD500 controller, Keyence Corporation, Osaka, Japan) with a step of 25 µm. The restorations were placed in a specific holder to ensure positioning reproducibility at each evaluation time. Raw data acquisition and processing were performed using a custom-developed software with C# language (Microsoft Visual Studio 2013, Microsoft Corporation, Redmond, WA, USA) coupled to a digital data-acquisition PCI board (NI PCI-6534, National Instruments Corporation, Austin, TX, USA). The resulting matrix of Z values was then transferred to the surface-matching software Geomagic Control 2015 (Geomagic Inc, Morrisville, NC, USA). The same operator (CW) performed all of the wear quantifications. Baseline scans were transformed into a computer-aided design format (STL) and recall scans were superimposed using a best-fit alignment algorithm. First, the software randomly selected and aligned 300 data points. After this rough alignment, fine alignment using 1000 additional data points was performed by iterative rotations and translations, minimizing the root-mean-squared difference between the two images. The deviation eliminator function was used to choose data points with a minimum deviation in the Z-axis. The matching process was considered acceptable if the root mean square was inferior to 20 µm. Only scans that successfully passed this matching process step were used for the wear analysis.

To prevent bias in the wear measurement related to artifacts or surface pollution, a threshold value of 150 µm was defined, leading to the exclusion of points with a measured difference superior to 150 µm from the wear evaluation. An additional control for adequate matching was the distribution of the z-values in the areas that were not subjected to wear (for example, occlusal grooves). In these areas, data points with a difference in z-values superior to 15 µm were excluded. A mean wear value was registered both for the entire occlusal surface and for each occlusal contact area (OCA), which were identified from the clinical pictures. These areas were digitally designed on each baseline scan using a mask.

Accuracy and precision calibration

The accuracy and precision of the method were assessed in a series of three experiments using the reference-free superimposition algorithm of Geomagic software according to the protocol proposed by Rosin et al. [36]: (1) precision of the automatic 3D superimposition algorithm, (2) precision of the 3D data acquisition, and (3) precision of the reference-free 3D superimposition.

2.6. Statistical analysis

The results are presented as means and standard deviations (SD) for the continuous variables and as frequency tables for the categorical variables. Comparisons between two categorical variables were done using Fisher's exact test. Statistical analysis differences between the experimental groups were assessed using InStat software (GraphPad), SAS version 9.4. An additional Kaplan-Meier analysis of the survival and success rates was performed.

3. Results

3.1. Clinical data on patients and restorations

A total of 47 patients were recruited (14 male and 33 female), with a mean age of 54.34 years (SD 15.32). Overall, 75 restorations corresponding to 101 elements were included during the inclusion period from February 2014 to December 2015. Sample descriptions in terms of patients, restorations, tooth elements, antagonists, and *ex vivo* analyzed occlusal areas are presented in Table 1. At 2 years, 45 patients and 95 elements were evaluated. After 2 years, 1 patient dropped out of the study.

The patients presenting bruxism clinical signs represented 61.7% of the cohort. All presented abnormal attrition wear facets. Among those patients, 19.1% had a nightguard but only one regularly wore it. Finally, 34% of patients presented unfavorable occlusal relationships.

3.2. Clinical outcomes

3.2.1. Restoration evaluation

The restorations (n=75) had a Kaplan-Meier survival rate (which comprises all restorations still in the mouth even if failed) of 93.3%±2.9% (5 restorations were lost) (Figure 2a) and a Kaplan-Meier success rate (which takes into account all failed restorations) of 81.8%±4.7% (Figure 3a). 80% of the catastrophic failures and 76.9% of all of the complications occurred in patients with clinical signs of bruxism, while 20% of the catastrophic failures and 23.1% of all of the complications occurred in patients with unfavorable occlusal relationships. Those complications are presented in Table 2. The debonding issue, which is at the origin of most failures, was significantly related to the type resin composite cement used for titanium base bonding (*p*=0.0046) and was solved replacing RelyX Ultimate by Multilink Hybrid Abutment (Ivoclar Vivadent AG, Schaan, Liechtenstein). If not considering the tooth-supported crown debonding since crowns on the natural teeth were provisionally cemented for the study purpose, the success rate was 86.7%.

Restorations placed in the patients with bruxism clinical signs had a Kaplan-Meier survival rate of 92.3%±3.7% and a Kaplan-Meier success rate of 79.6%±5.9%, while those placed in the patients without bruxism clinical signs had a Kaplan-Meier survival rate of 95.7%±4.2% (Figure 2d) and a Kaplan-Meier success rate of 87.0%±7.0% (Figure 3d). However, this difference was not statistically significant regarding the survival rate (*p*=0.60) or the success rate (*p*=0.55)

Considering the results by the type of restoration, implant-supported FPD's had a survival rate of 100%, implant-supported crowns had a Kaplan-Meier survival rate of 95.8%±3.0% (Figure 2b), and tooth-supported crowns had a Kaplan-Meier survival rate of 76.9%±12.0% (Figure 2c).

Kaplan-Meier success rate for implant-supported FPD's was 100%, 84.3%±5.6% for implant-supported crowns (Figure 3b) and 53.8%±13.8% for tooth-supported crowns (Figure 3c), or 76.9% if debonding of provisionally cemented crowns were not considered.

The FDI scores of the restorations are presented in Table 3. Regarding the aesthetic properties, zirconia restorations showed excellent or good results (Figure 1c) except for color match and translucency. Indeed, 65.2% were judged too bright but acceptable by the dentist. Regarding the functional properties, zirconia monolithic restorations showed excellent or good results, except for the proximal contact points that were evaluated as too weak for 4.2% of the restorations. The biological properties demonstrated excellent results.

3.2.2. Antagonistic tooth evaluation

Three antagonistic teeth were lost due to root fracture (1.6%) or severe periodontal disease (0.8%) (Table 2). One was a monolithic zirconia restoration (Figure 4h). These teeth were weakened by post and core restoration or already had periodontal disease before treatment. Two minor composite chippings were detected and repaired (1.6%) (Figure 5a). Monolithic zirconia restorations that were located in the front of those teeth did not show any failures.

3.2.3. Patient satisfaction level

The FDI scores of the patients' views showed that 60.0% rated their satisfaction level as excellent, while 100% of the restorations were rated as acceptable. Only 2.1% reported minor esthetic issues because they judged their crowns as too bright.

3.3. *Ex vivo* analyses

Two screw-retained crowns were not *ex vivo* analyzed because their removal was not possible from a technical point of view.

3.3.1. SEM observations

After 6 months, 70.2% of the glazed cusps presented glaze wear with variable extents on the contact point areas. Glaze wear was observed in 100% of the glazed occlusal contact points after 1 year (Figure 6).

3.3.2. Profilometry

Accuracy and precision calibration

For 3-dimensional measurements of zirconia wear, the intrinsic errors of the superimposition program of the software (experiment 1) resulted in an accuracy of 0.01±0.01 µm (the accuracy is reported as the mean of the multiple measures and the precision corresponds to the standard deviation [37]). Assessment of the three-dimensional data acquisition produced differences in height of 0.09±0.09 µm (experiment 2). The superimposition when the position of the crown within the laser scanner was altered after each scanning procedure (experiment 3) resulted in an accuracy of 0.47±0.17 µm. The vertical resolution of the laser scanner was 15 µm.

After 2 years, the wear of the zirconia prostheses occlusal face was inferior to the accuracy threshold of the measurement chain (15 µm). However, wear was detectable on the occlusal contact points specifically for 15% of the investigated teeth (7 teeth) (Figure 7). Finally, 16% of the scans were unusable for wear quantification due to their insufficient quality.

4. Discussion

Second-generation zirconia is widely used for posterior monolithic restorations but currently the clinical background is lacking and only one study included patients with bruxism, while manufacturers often recommend full zirconia restorations for this indication [15–28].

This study included 101 restorations in 47 patients followed for 2 years in a sample including 61.7% of patients with clinical signs of bruxism registered with a standard non-instrumental approach of bruxism diagnosis, including a clinical inspection and self-report, notably following the criteria of the American Academy of Sleep Medicine [34,38,39]. However, bruxism diagnosis is complex and inaccurate, and if the employed criteria are graded 2 on 3 in terms of assessment validity (meaning "probable sleep/awake bruxism"), polysomnography is recommended to confirm diagnosis [33], which was not possible in this large-scale clinical study. All of the patients recorded as bruxers presented abnormal attrition wear facets and reported teeth grinding during the night or day, which means that the presence of bruxism is probable but can engender some false positives [38]. Consequently, it can explain the high proportion of patients considered bruxers compared to the literature data, but those data are restricted, particularly for awake bruxism, and diagnostic criteria are greatly heterogeneous (reported prevalence is 22-30% for awake bruxism and 1-15% for sleep bruxism) [40].

Restorations (n=75) had a global survival rate of 93.3%±2.9% (Figure 2a) and a global success rate of 81.8%±4.7% (Figure 3a), while patients with clinical signs of bruxism exhibited a lower restoration survival (92.3% versus 95.7%) (Figure 2d) and success (79.6% versus 87.0%) (Figure 3d) rates. If this difference was not significant (p=0.60 and p=0.55 for the survival and the success rate, respectively), long-term results are needed to study the influence of this parameter on restoration performance.

Implant-supported FPDs (n=14) showed excellent results with a survival rate of 100%. This can be explained by the fact that splinting implants improve stress distribution [41]. Cardelli et al. presented encouraging results after 1 year in a pilot study of 2 patients rehabilitated with monolithic zirconia full-arch fixed prostheses on implants [17], as did Rojas Vizcaya in a 2- to 7-year retrospective study about 20 double full-arch prostheses [22]. The observed survival rate was better than the reported estimated 5-year survival rate of veneered zirconia and metal-ceramic implant FPDs (93.0% and 98.7%, respectively) [42], knowing that 4.1% of the zirconia implant-supported FPDs were lost due to ceramic or framework fractures.

Implant-supported crowns (n=48) showed a survival rate of 95.8%±3.0% (Figure 2b), which is inferior to the 100% 3-yr survival rate reported in the recent study of De Angelis et al. about 19 screw-retained restorations, which did not include patients with bruxism and constitutes, to author's knowledge, the only published study about monolithic zirconia implant crowns [18]. Loss of osseointegration was the only cause of failure, engendering 4.2% of implant loss. Implant loss was characterized by implant mobility as well as bone cratering visible on the radiograph. One implant was lost in a patient with bruxism signs who had a history of periodontal disease and peri-implantitis, and the other implant was a narrow implant that presented a beginning of bone loss after implantation. The implant-supported crown survival rate in this study was globally lower than the reported estimated 5-year survival rate of veneered zirconia and metal-ceramic implant crowns described in a recent meta-analysis (97.6% and 98.3%, respectively) [43]. In this review, the authors underlined the prevalence of veneering ceramic fractures for the zirconia crowns (2.8%) and noticed that 3.3% of the implants supporting metal-ceramic crowns and 4.3% of the implants supporting zirconia-based crowns experienced significant bone loss, defined as marginal bone levels more the 2 mm below what can be expected as normal bone remodeling. One hypothesis to explain the lower results of the present study is that in cases of high occlusal stress, the veneering ceramic constitutes the weak link of the restoration and can act as a breaker, while in cases of monolithic restoration, zirconia being stiff, the stress is transmitted to the implant, engendering a higher rate of implant failures.

Tooth-supported crowns (n=13) exhibited the worst survival rate: 76.9%±12.0 (Figure 2c). Failures were related to crown fracture (7.7%) (Figure 5b), core fracture (7.7%) (Figure 5c) and root fracture (7.7%) (Figure 4h). The tooth, which showed a root fracture, had a screw-retained monolithic zirconia crown as an antagonist. The present results contrast with the literature. Bömicke et al. reported a 98.5% survival rate after 3 years in a prospective study of 82 monolithic crowns on natural teeth [16]. In that study, complications encountered also included the loss of retention and vertical root fracture. In another prospective study, Batson et al. reported a 100% survival rate for 10 monolithic second-generation zirconia crowns over 1 year [15]. The survival rate of the present study was also lower than the reported estimated 5-year survival rate of veneered zirconia, metal-ceramic, and lithium-disilicate reinforced glass ceramic crowns (96.0%, 94.7%, and 96.6%, respectively) [44]. In a systematic review by Sailer et al., crown fractures were less reported (0.4% for veneered zirconia crowns, 0.03%

for metal-ceramic crowns, and 2.3% for lithium-disilicate reinforced glass ceramic crowns). Moreover, tooth fracture was predominantly found for metal-ceramic crowns (1.2%), and this complication occurred significantly less frequently for all ceramics. The higher rate of failures observed in the present study could be explained by the small sample size, which did not allow us to draw some significant conclusions, and by the inclusion of patients with high occlusal stress since most failures occurred in those patients (Figure 2d). Indeed, in that case, the weak link can be the crown if the zirconia thickness is low, the core (core fracture), or the tooth (root fracture). The inclusion of such patients in clinical studies is crucial to validate techniques and procedures. Only one study included those patients and reported 1 crown fracture after 2 years in a case series including 84 crowns in 13 heavy grinders [28].

In the present study, the Kaplan-Meier success rate was only 81.8%±4.7%) at 2 years (Figure 3a). Prosthesis debonding (9.3%) impaired the success rate, but those failures were treated by performing a new bonding procedure. This event was anticipated for tooth-supported crowns as they were cemented with temporary cement for the study purposes. Implant-supported restorations debonding between zirconia crowns and titanium abutments were encountered only with RelyX Ultimate resin composite cement (28.0% of screw-retained restorations were cemented with RelyX Ultimate). For the new bonding procedure, Multilink Hybrid Abutment (Ivoclar Vivadent AG, Schaan, Liechtenstein) was preferred and showed better results.

The presence of implant loss, minor chipping (Figure 5d), root as restoration fractures of antagonistic teeth, which were not considered in the success rate, must also be highlighted. One hypothesis is that zirconia's high stiffness and lack of resilience does not allow for occlusal stress absorption, as this stress is transferred to the implant, the tooth, or its antagonist. Indeed, most complications (76.9%) occurred in patients with bruxism clinical signs and only one regularly wore a nightguard as protection. This can support using a damping material when planning treatment in patients with bruxism to avoid any weak link effect [46,47]. Figure 4 presents the history of a patient who showed unfavorable occlusal relationships and bruxism over 12 years. This clinical case illustrates the fact that improving material resistance does not necessary enhance treatment performance.

However, clinical FDI evaluations after 2 years were very good. Evaluators' assessments were high, even if a significant proportion of proximal contacts were judged as too weak. Experienced handling of the design software solved this issue. All of the biological aspects of the FDI criteria had high scores, showing the excellent biocompatibility of zirconia. Evaluators gave a lower score to aesthetic results than patients, who reported a high satisfaction rate. This result is consistent with other reports [15,16] and confirms that second-generation zirconia is appropriate for posterior restorations in terms of aesthetics.

Finally, the present study protocol allowed for wear quantification with laser profilometry performed directly on the restorations to avoid bias due to the use of replicas and for direct SEM observations to evaluate glaze wear in occlusal contact areas. Regarding wear, no zirconia wear was observable after two years, with respect to the accuracy and precision of the wear quantification experimental set up (15 μm). Laser profilometry and superimposition of scans is reputedly the best technique for clinical wear quantification [37], but unusable scans are often described, ranging from 14% to 31% [48–51]. Wear measurement was effective since quantification was conducted from the direct acquisition of the restoration surfaces and not from replicas as is frequently done for the measurement of antagonist tooth wear [17,20,30]. Indeed, the replica technique may explain the difference between the low zirconia wear reported in the present study. Cardelli et al. reported a 63 μm vertical loss when zirconia opposed enamel and a 19 μm vertical loss when zirconia opposed composite resin [17]. Glaze wear was highlighted on 70.2% of occlusal contact points areas after 6 months and on 100% after one year, which was predicted by Denry and Kelly [12]. Investigations regarding the influence of the finishing procedure showed that polishing should be preferred to glazing [52–61], which engenders a higher surface roughness and antagonistic tooth wear [62,63].

Limitations of the present study include the low number of FPDs (n=14) and cemented crowns on teeth (n=13), and the provisional cementation of those crowns due to study design.

5. Conclusion

In this prospective study, the global survival rate of the restorations was 93.3% after 2 years, FPDs having shown an excellent survival rate (100%) compared to crowns (95.8% for implant crowns and 76.9% for crowns on natural teeth), despite a high number of patients (61.7%) showing clinical signs of bruxism. The inclusion of patients with bruxism in clinical studies is rare but crucial to test the validity of new materials and techniques. It must be underlined that the sample size for implant FPDs (n=14) and crowns on natural teeth (n=13) was small and that further research is needed to confirm the present results. On the other hand, this study brings significant short-term data about 48 monolithic zirconia implant crowns, while the literature is sparse in that field and patients with bruxism were not examined. Zirconia wear was inferior to 15 μm after 2 years. Glaze wear was observed on all of the occlusal areas after 1 year, but not on the buccal and lingual/palatal faces. Clinical evaluation of the restorations showed good results after 2 years from aesthetic, functional, and biological perspectives. One crown fracture was reported. However, the treatment success rate after two years (81.8%) was not as high as expected. Eighty percent of the catastrophic failures and most of the complications (76.9%) occurred in patients with clinical signs of bruxism, who exhibited a not significantly lower restoration survival (92.3% versus 95.7%) and success (79.6% versus 87.0%) rates at two years. The present results underscore, from the authors' point of view, a weakness of full zirconia restorations, which are strong but stiff and unable to absorb stresses. This could be suspected to promote the "weak link theory," that is, a breaker effect on the weaker parts of the system, which can be the bonding interface, the supporting tooth, the supporting implant, or the antagonistic teeth/implants. Consequently, single-unit full zirconia restorations should be used with caution until further and long-term research is conducted considering samples, which do not exclude bruxers.

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Tables

Table 1: Sample description of patients, restorations, tooth elements, antagonists, and *ex vivo* analyzed occlusal areas. GCC: glazed centric cusps, UCC: unglazed centric cusps, GNCC: glazed non-centric cusps, UNCC: unglazed non-centric cusps. Sample description: 47 patients, 101 elements, 75 restorations, and 326 occlusal contact point areas.

Sample description	% (n)
Patients (n = 47)	
Sex	
Female	70.2 (33)
Male	29.8 (14)
Bruxism (self-report + clinical inspection)	61.7 (29)
Nightguard	19.1 (9)
Restorations (n = 75)	
Crowns	
Implant screw-retained crowns	58.7 (44)
Implant cemented crowns	5.3 (4)
Cemented crowns on teeth	17,3 (13)
Bridges	
Screw-retained bridges on two implants	17.3 (13)
3-element	14.7 (11)
2-element	2.7 (2)
3-element cemented bridge on two implants	1.4 (1)
Tooth elements (n = 101)	
Support	
Tooth	12.9 (13)
Implant	87.1 (88)
Tooth type	
Premolar	38.6 (39)
Molar	61.4 (62)
***Ex-vivo* analyzed occlusal areas (n = 326)**	
GCC	26.4 (86)
UCC	23.9 (78)
GNCC	29.1 (95)
UNCC	20.6 (67)
Antagonists (n=127)	
Tooth	88.2 (112)
Implant	11.8 (15)

Table 2: Percentage of complications.

Complications	% (n)
Restorations	
Screw-retained restoration debonding from titanium base	5.3 (4)
Cemented restoration debonding	4.0 (3)
Implant loss	2.7 (2)
Crown fracture	1.3 (1)
Root fracture	1.3 (1)
Composite core fracture	1.3 (1)
Minor chipping	1.3 (1)
Antagonists	
Root fracture	1.6 (2)
Severe periodontal disease	0.8 (1)
Minor composite chipping	1.6 (2)

Table 3: FDI scores of the aesthetic, functional, and biological properties after 2 years, in percentage (n=95). Postoperative sensitivity, recurrence of caries, and tooth integrity were evaluated only for teeth (n=10).

	Clinically Excellent % (n)	Clinically Good % (n)	Clinically Sufficient % (n)	Clinically Unsatisfactory % (n)	Clinically poor % (n)	Acceptable %	Unacceptable %
A. Esthetic properties						**100**	
Surface luster	94,7 (90)	5,3 (5)					
Staining							
a. surface	96,8 (92)	3,2 (3)					
b. margin	96,8 (92)	3,2 (3)					
Color match and translucency	5,3 (5)	29,5 (28)	65,2 (62)				
Esthetic anatomical form	44,2 (42)	47,4 (45)	8,4 (8)				
B. Functional properties						**95,8**	**4,2**
Fracture of material and retention	99 (94)		1 (1)				
Marginal adaptation	95,8 (91)	4,2 (4)					
Approximal anatomical form							
a. contact point	65,2 (62)	3,2 (3)	27,4 (26)	4,2 (4)			
b. contour	99 (94)	1 (1)					
Radiographic examination	100 (95)						
Patient's view	60 (57)	32,6 (31)	7,4 (7)				
C. Biological properties						**89**	**11**
Postoperative sensitivity and tooth vitality	90 (9)			10 (1)			
Recurrence of caries, erosion, abfraction	100 (10)						
Tooth integrity	100 (10)						
Periodontal response	98 (93)	1 (1)			1 (1)		
Adjacent mucosa	99 (94)		1 (1)				
Oral and general health	100 (95)						

Figures

Figure 1: Screw-retained crown on implant (tooth #34). a) Landmarking with permanent ink of areas, which will not be glazed. b) Occlusal contact points. c) Aesthetic integration.

Figure 2: Kaplan-Meier survival rate. a) Global. b) Implant-supported crowns. c) Tooth-supported crowns. d) Comparison between restorations inserted in patients with (in blue) or without parafunctional habits (in red). Dotted lines represent 95% confidence intervals.

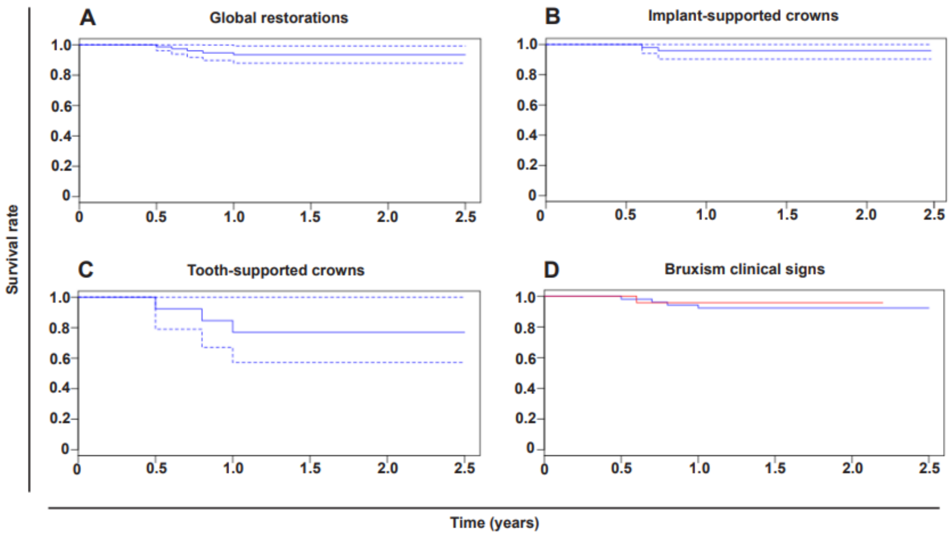

Figure 3: Kaplan-Meier success rate. a) Global. b) Implant-supported crowns. c) Tooth-supported crowns. d) Comparison between restorations inserted in patients with (in red) or without parafunctional habits (in blue). Dotted lines represent 95% confidence intervals.

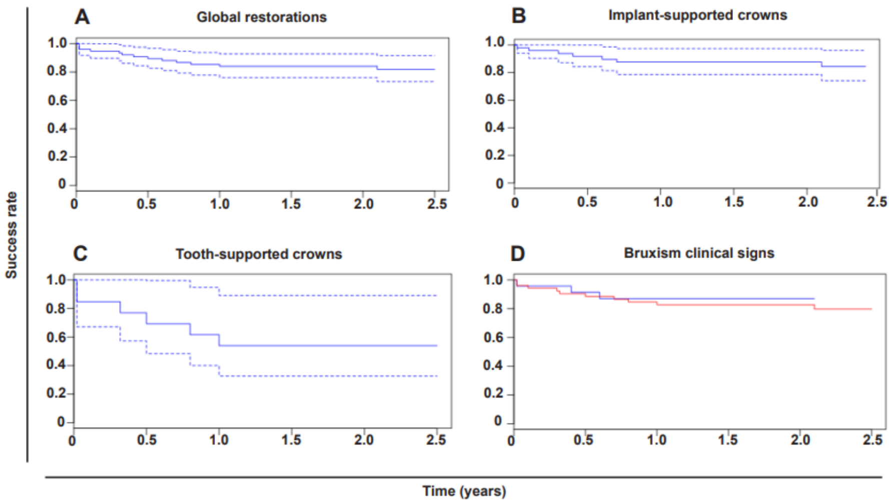

Figure 4: Patient. (a and b) Root fracture #36 and extraction. (c) Realization of veneered zirconia crowns on teeth #26, #27, and #37 and implant #36. (d and e) Chipping (arrowed) on #26 and #36 after 6 months and on #27 after 3 years. (f) Root fracture #27 after 8 years. (g) Monolithic zirconia crowns #26, #27, and #36. (h) Root fracture on tooth #26 after 1 year. (i) Use of polymer-infiltrated ceramic network (PICN) material for crowns on implant #26 and implant #37 at a 2-year follow-up. Full zirconia (FZ) restorations on implant #27 and implant #36 at a 3-year follow-up.

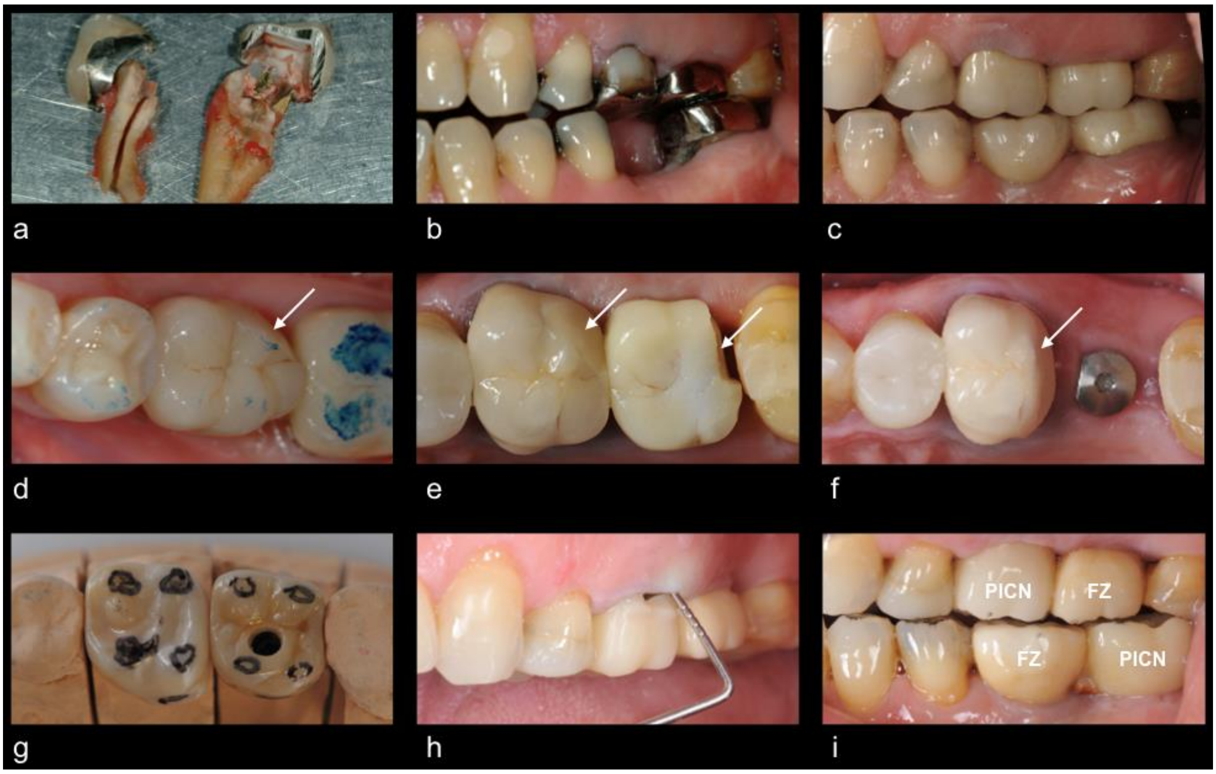

Figure 5: Failures. a) Composite chipping on an antagonistic tooth (tooth #47). b) Monolithic zirconia crown fracture (tooth #14), with a framework, which was not particularly thin. c) Core debonding (tooth #16). d) Minor chipping (tooth #46).

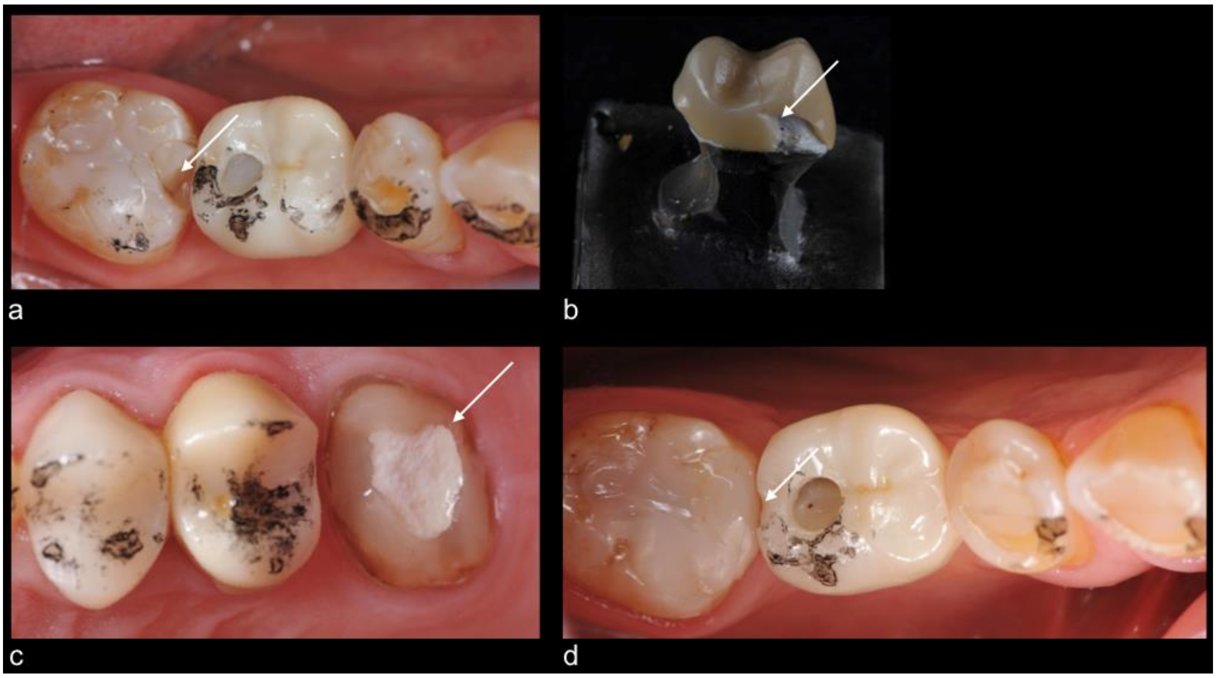

Figure 6: Glaze wear. Glazed areas are darker on baseline SEM images (baseline). Arrows indicate wear zones after 1 and 2 years.

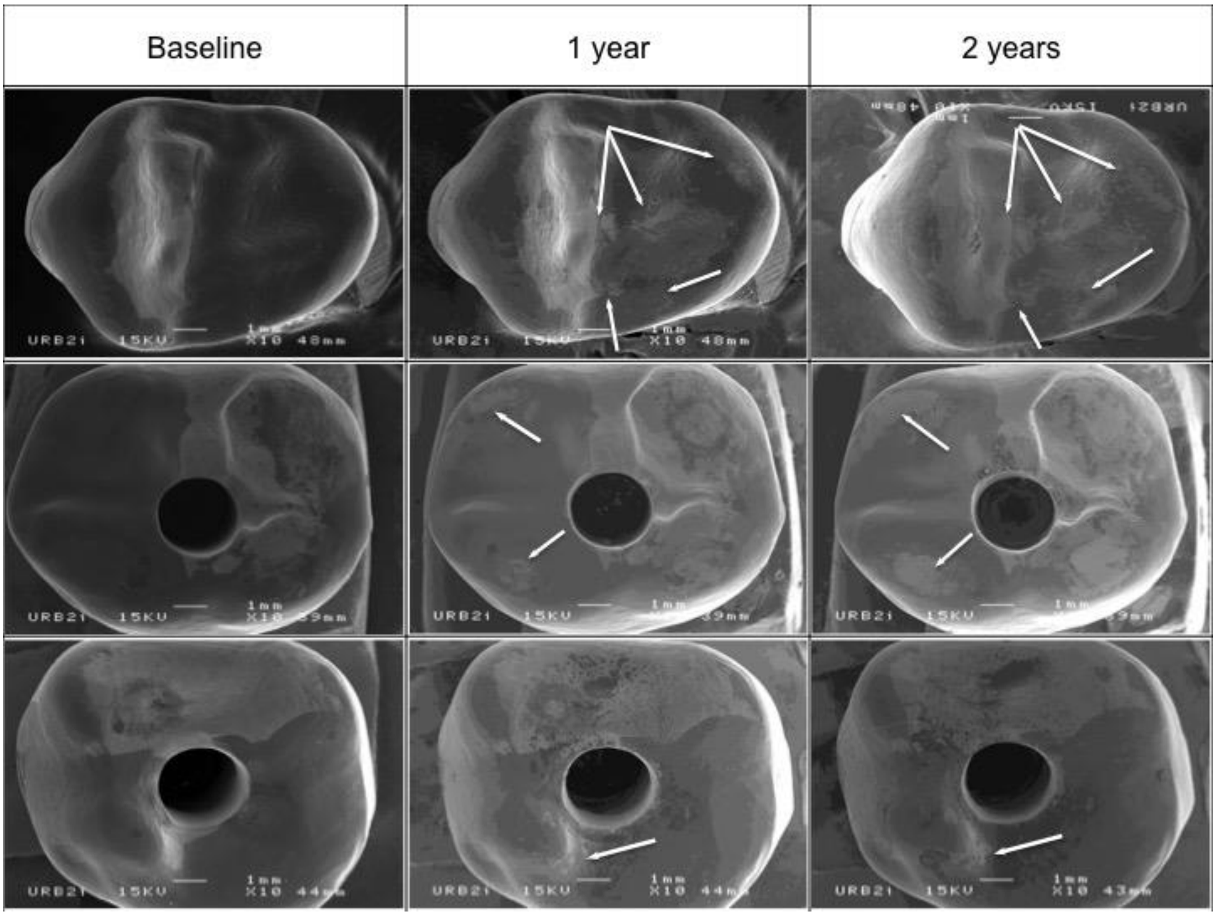

Figure 7: Wear on occlusal contact areas, screenshot of 3D measurement, and SEM. Mean vertical wear in occlusal contact areas was 19 µm for tooth #16.