Clinical Reliability of CAD/CAM Cross-Arch Zirconia Bridges on Immediately Loaded Implants Placed with Computer-Assisted/Template-Guided Surgery: A Retrospective Study with a Follow-Up between 3 and 5 Years

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ABSTRACT

Purpose: The purpose of this study is to retrospectively evaluate the implant and prosthetic survival and success rates of zirconia-based, implant-supported, screw-retained, cross-arch restorations up to 5 years after placement.

Materials and Methods: Twenty-two consecutive edentulous patients (11 males and females, each; mean age 68.3 years) received 26 CAD/CAM cross-arch zirconia implant bridges (NobelProcera™ Implant Bridge Zirconia; Nobel Biocare AG, Zurich, Switzerland) supported by 4 to 10 implants each. All patients were followed for at least 3 years (range 36–60 months, mean 42.3 months). Clinical assessments were scheduled every 4 months during hygiene maintenance. Outcomes were implant and prosthetic survival rates, prosthetic success rate, any observed clinical complications, patient satisfaction, and soft tissue parameters. Fisher's exact test was used to assess associations between categorical variables.

Results: No dropouts occurred. The overall implant and prostheses survival rate up to 5 years was 100%. Three out of 26 restorations (five out of three hundred forty eight dental units) showed an adhesive chip-off fracture of the veneering ceramic, scoring a cumulative prosthetic success rate of 88.5% at the prosthetic level and 98.6% at the unit level. All 22 patients were functionally and aesthetically highly satisfied with their restorations. Successful soft tissue parameters were found around all implants.

Conclusions: Industrially manufactured, zirconia-based, implant-supported, screw-retained, cross-arch restorations are a viable alternative to conventionally manufactured porcelain-fused-to-metal restorations for rehabilitating the edentulous patient.

KEY WORDS: CAD/CAM, complications, cross-arch fixed dental prosthesis, dental implants, edentulous, zirconia

INTRODUCTION

The concept of osseointegration has undoubtedly been one of the most significant scientific breakthroughs in dentistry over recent decades.[1] The predictability and success of implant treatment has increased as a result of the continuing evolution of implant designs, bioactive surfaces, prosthetic materials, and technologies.[2] Patient demands for long-term function, and aesthetics challenge the clinicians to deliver an implant-supported restoration in harmony with the individual's facial personality and perfectly integrated into the intraoral environment.[3–5] Nowadays, the focus of dentistry has shifted toward restoration that is functionally stable and indistinguishable from the neighboring dentition over time.[6] Healthy soft tissue integration and its long-term maintenance is mandatory to deliver a long-lasting and aesthetically pleasing implant-supported prostheses.[7]

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The ongoing research for aesthetic and biocompatible materials has favored using all-ceramic reconstructions for fixed dental prostheses (FDPs) as alternatives to conventional porcelain-fused-to-metal (PFM) prostheses.[8] High-strength metal-oxide ceramics have been developed to overcome the mechanical drawbacks and high fracture rates of earlier all-ceramic systems.[9–12] Zirconium oxide (ZrO_2 or zirconia) has gained increasing popularity in contemporary dentistry due to its high biocompatibility,[13,14] low plaque surface adhesion,[15] high flexural strength,[16] absence of mucosal discoloration,[17] and aesthetic properties.[18,19] Yttria-stabilized zirconium dioxide (Y-TZP) is more biocompatible than high-gold cast alloys, reducing bacterial and plaque adhesion and preventing soft tissue inflammation.[17,20–22] Thus, Y-TZP contributes to achieving healthy soft tissue integration of implant-supported restorations, thus improving long-term stability of the marginal bone.[22,23] Zirconia-based all-ceramics are currently used to fabricate copings and implant abutments and for partial and complete arch frameworks on both natural teeth and implants, in both anterior and posterior oral cavity areas.[22–28] Laboratory and clinical studies have shown substantially increased flexural strength and fracture toughness for Y-TZP FDPs compared with other ceramic materials and reported prosthetic survival and success rates comparable with conventional PFM FDPs.[29–31] Nevertheless, there is still a significant lack of medium- to long-term data on zirconia-based implant-supported restorations, and most clinical studies have investigated single-crown restorations and FDPs supported mainly by natural teeth.[2,8,32]

The latest published systematic review on survival and complications of zirconia frameworks, based on 11 clinical studies, concluded that porcelain-fused-to-zirconia (PFZ) FDPs is an alternative to conventional metal ceramic FDPs in the anterior and posterior dentition, but only short-term clinical data were available.[32] Only one randomized controlled clinical trial[11] reported comparative preliminary data on the survival and success rates of PFM and PFZ tooth-supported three- to five-unit FPDs after 3 years in function. That study reported no difference in framework survival, whereas the PFZ success rate was lower due to an increased risk of chipping the porcelain veneer.[11]

The main clinical concern reported in the literature regarding Y-TZP used as a framework material is a higher incidence of veneering porcelain chip-off fracture rates[8,19,32] ranging from 15% to 54% over a 3- to 5-year period[8,33] versus 2.9% to 8.8% ceramic fracture rates observed in conventional tooth- and implant-supported metal-ceramic restorations over 5 years.[34] Zirconia-based FDPs exhibit 7% higher veneer chipping when directly compared with metal-based FDPs, and core fracture occurred in less than 1% of the zirconia-based FDPs, whereas none of the metal cores were fractured.[8]

A 3-year study on cement-retained, zirconia-based, implant-supported 2- to 5-unit FDPs revealed a veneering porcelain chipping rate of up to 53% after 12 months.[35] Nevertheless, to the best of our knowledge, only two prospective studies reported clinical and technical data on zirconia-based, implant-supported, cross-arch restorations.[23,27] A 3-year study on cement-retained, cross-arch, zirconia implant bridges observed no fractures of Y-TZP frameworks, full patient satisfaction but a high ceramic chipping rate of 34% assessed at the unit level (34/99 prosthetic units).[27] In a follow-up study of screw-retained, cross-arch, zirconia implant bridges,[23] the Y-TZP framework survival rate was 100%, validating PFZ FDPs as a viable prosthetic treatment option after 2 to 4 years of function. Chip-off fractures were a frequent complication, with a 31.25% chipping rate assessed at the prosthesis level.[23] Despite this mechanical complication, patient satisfaction, favorable soft tissue response, and high aesthetics outcome were noted.[23] Several hypotheses concerning the causes of porcelain veneer chipping highlight the importance of factors such as framework design, laboratory handling, baking procedures, and ceramic mechanical properties.[23,25,30–34]

This study aimed to retrospectively assess the implant survival and prosthetic success and survival rates of implant-supported, screw-retained, cross-arch, zirconia-based restorations (SCAZIRs) up to 5 years in function. The null hypothesis was that the different timing of implant placement (immediate vs delayed), type of implant connection (internal vs external), type of arch (mandible vs maxilla), and number of supporting implants and span of bridge (cantilever vs full support) do not influence SCAZIR clinical outcomes. This study follows the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines (http://www.strobe-statement.org).[36]

MATERIALS AND METHODS

This retrospective study evaluated data collected from pivotal prospective studies that included 22 consecutive patients of both sexes, with at least one edentulous arch, aged ≥18 years, treated with industrially manufactured SCAZIRs, supported by 4 to 10 implants each, and followed for ≥3 years of function (range 36–60 months; mean 42.3 months). All patients were treated in one specialized rehabilitation center (Department of Oral Rehabilitation, University of Rome Tor Vergata, Italy) between October 2007 and December 2009. One clinician performed all surgical and prosthetic procedures, and one dental laboratory that was qualified in computer-aided designed/computer-assisted manufacturing (CAD/CAM) technology and zirconium oxide framework handling manufactured all restorations. The investigation was conducted according to the tenets of the Helsinki Declaration and with written informed consent of the participants.

Inclusion criteria were: patients who received an implant-supported, screw-retained, cross-arch, zirconia-based restoration with ≥36 months of follow-up; a full-mouth bleeding on probing and a full-mouth plaque index ≤25%; a residual alveolar crest sufficient to accommodate an implant of 10-mm length and 3.5-mm width following a computed tomography (CT) scan; and stable occlusal relationship. Exclusion criteria were: general medical (American Society of Anesthesiologist, ASA, class III or IV) and/or psychiatric contraindications, pregnancy or nursing, any interfering medication such as steroid therapy or bisphosphonate therapy, alcohol or drug abuse, heavy smoking (>10 cigarettes/day), radiation therapy to head or neck region within 5 years, bone augmentation procedures, high and moderate parafunctional activity,[37] absence of teeth/denture in the opposite jaw, cantilever lengths greater than 10 mm, untreated periodontitis, poor oral hygiene, and unavailability for regular follow-ups.

One independent examiner conducted a retrospective chart analysis of 25 consecutively treated patients, rehabilitated with implant-supported, screw-retained, cross-arch, zirconia-based restorations. Twenty-two patients (11 females and 11 males) of the 25 examined, with an overall mean age of 68.3 years (females: 68.2, range 50–83; males: 65.7, range 58–81) at definitive prosthesis delivery, met the inclusion criteria. Three patients (14%) were smokers, and two patients (9%) showed signs of occasional parafunctional activity (based on history and clinical examination). Eighteen patients had one arch to be fully restored, whereas the remaining four patients received both maxillary and mandibular restorations, totaling 26 cross-arch zirconia implant bridges. Restorations were supported by 4 to 10 implants, for a total of 170 implants. Forty-four implants (10 tilted and 34 axial) in eight patients were inserted in fresh extraction sockets. Compromised teeth with a poor prognosis were atraumatically extracted and the socket debrided. The 34 immediate postextractive axial implants were placed 1 mm deeper than the buccal bone crest, engaging at least 3 mm of healed bone, apical to the root apex, to achieve an adequate primary stability of at least 30 Ncm. The remaining gap was filled with autogenous bone to reduce resorption. Six of 10 tilted implants engaged the extraction socket only in the most coronal part, whereas the remaining four implants were inserted through it only with their body.

Jaw distribution of the restorations/implants is reported in Table 1. All the 26 edentulous arches were prosthetically restored and are included in the study. Each arch rehabilitated with a SCAZIR consisted of 12 to 16 dental units, resulting in a total of three hundred forty eight units. For descriptive analysis, each edentulous arch, corresponding to one SCAZIR, was the statistical unit. The opposite arches presented implant-supported PFZ or PFM full-arch restorations ($n = 14$), removable partial dentures ($n = 2$), natural dentition ($n = 9$), and metal-composite restoration ($n = 1$). Seven of 26 restorations presented distal cantilever not exceeding 10 mm. Zirconia frameworks were made according to established CAD/CAM protocols (NobelProcera® software; Nobel Biocare AG, Zurich, Switzerland) and were veneered with feldspathic porcelain (Noritake Cerabien Zirconia, CZR; Noritake Dental Supply Co., Limited, Aichi, Japan).

TABLE 1 Cross-Arch Zirconia Implant Bridges (Number of Implants For Each Restoration)

Maxilla	3 (4)	1 (5)	3 (6)	3 (8)	1 (9)	1 (10)	12 (78)
Mandible	4 (4)	2 (5)	2 (6)	3 (8)	3 (10)		14 (92)

Prosthetic Design and Fabrication Protocol

Before implant placement, patients underwent a CT scan (LightSpeed VCT; GE Healthcare, Waukesha, WI, USA) or a cone beam CT (SCANORA® 3D; Soredex, Tuusula, Finland) with a double-scan protocol,[38] to accurately plan implant positioning according to the biomechanical, biological, and aesthetic demands of the patient and perform full-arch implant placement in a minimally invasive fashion. Four different implant types were used (Table 2); however, all implants had the same porous anodized surface (TiUnite®, Nobel Biocare AG). Implants were placed by computer-assisted template-guided surgery (NobelGuide®, Nobel Biocare AG). Prefabricated metal-reinforced, screw-retained, acrylic resin, interim restorations were delivered immediately in all patients. Marginal precision, retention, and stability were obtained by relining with an autopolymerizing polyurethane resin (Voco GmbH, Cuxhaven, Germany) on the nonengaging titanium temporary abutments (Temporary Abutment Non-Engaging, Nobel Biocare AG) screwed onto the implants. Centric and lateral contacts were assessed by 40 µm articulating paper (Bausch Articulating Paper, Köln, Germany), until light occlusal contacts, uniformly distributed on the entire prosthetic arch, were obtained.

Following an uneventful healing period of 3 and 4 months in the mandible and the maxilla, respectively, definitive impressions were taken at the implant level, using an open-tray implant impression. Impression copings (Nobel Biocare, AG) were connected and tightened at 15-Ncm setting using a torque control device (Torq Control®; Anthogyr, Sallanches, France). Digital radiographs verified complete seating of the impression copying. Impressions were made using custom impression trays (Elite® LC tray, Zhermack® SpA, Badia Polesine, Rovigo, Italy) and plaster (Snow White Plaster no. 2; Kerr, Romulus, MI, USA). Static and dynamic occlusal data (ARCUS®digma II; KaVo ITALIA s.r.l., Genova, Italy) were recorded to set a fully adjustable articulator.

New implant replicas (Nobel Biocare, AG) were connected with the impression copings and tightened to 15 Ncm. All definitive casts were made with the same materials (Gingifast Zhermark® SpA; Badia Polesine) and low-expansion type IV stone (FujiRock® EP; GC Europe, Lovanio, Belgium), according to manufacturer instructions.

Interim restorations were removed and screwed onto the master cast to transfer into a fully adjustable articulator the occlusion and the vertical dimension of each patient. Prosthetic volume and related aesthetic and phonetic information established during a healing period of 3 to 4 months were gathered from the temporary prosthesis by a silicone putty index. A cross-mounting technique was used to articulate the opposite arch cast with the interim restoration screwed onto the master cast, by means of an interocclusal jig. The provisional restoration provided functionally established anterior guidance of the patient that was recorded, customizing the anterior articulator guide table.[39]

Nonengaging abutments (Nobel Biocare, AG) were screwed on to the master cast and a low shrinkage acrylic resin (GC Pattern Resin™ LS; GC Europe N.V., Leuven, Belgium) was injected in the silicone index to obtain a full contour mock-up. The acrylic-resin framework was customized by a cutback procedure to ensure adequate support of veneering material and minimum connector thickness, as recommended by the manufacturer. Minor adjustments were made by wax, if necessary. The connector area of the cross-arch frameworks had a minimum cross-sectional area of 8 mm^2, with a minimum of 4 mm height and 2.5 mm width between units. To eliminate the shrinkage effect of the acrylic material, 0.1 mm cuts were made between implants and a small amount of acrylic material was used to reconnect the sections. The acrylic-wax framework was scanned using either of two technologies: tactile (Procera® Forte scanner; Nobel Biocare AG) or optical with a conoscopic holographic technique (NobelProcera™ scanner; Nobel Biocare AG) (Figure 1). The data obtained were digitized using system specific software (NobelProcera system; Nobel Biocare AG) and subsequently milled at a centralized production facility.

TABLE 2 Implant Distribution. Type of Implants (Number of Restorations/Number of Implants)

Maxilla	NobelSpeedy Groovy (2/17)	NobelActive (10/61)			12 (78)
Mandible	NobelSpeedy Groovy (7/55)	NobelReplace Tapered Groovy (1/5)	NobelSpeedy Replace (1/8)	NobelActive (5/24)	14 (92)

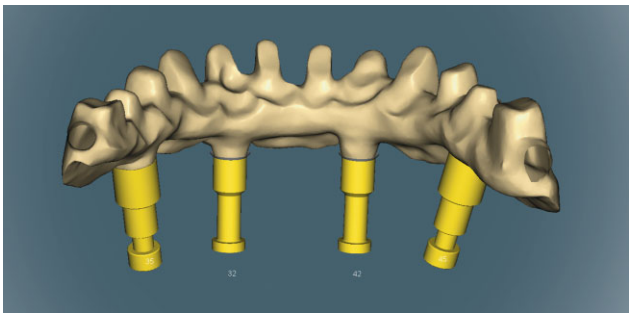

Figure 1 CAD calix-shape design of the zirconia framework.

The fit of each cross-arch zirconia framework (Zirconia Implant Bridge; Nobel Biocare AG) was assessed intraorally according to established criteria, such as strain-free screwing, as well as no open margins at the clinical and radiographic examinations during the Sheffield one-screw test performed chair-side (framework correctly in place without vertical and horizontal discrepancy at close-up inspection and periapical radiographs).[40,41]

Zirconia framework grinding was performed with dedicated-zirconia burs (ZR-Diamonds, Komet Italy s.r.l., Milan, Italy) under copious irrigation of a mixture of cutting oils (50%) (Artiglio s.n.c., Parma, Italy) and eucalyptol (50%) to minimize "thermal stress." Frameworks were shaped with a cross-section calyx shape (Figure 2), and silicone diamond wheels (Noritake Point SC-51 or SD-61, Noritake) were used to polishing the framework surface.

Surface conditioning of the zirconia framework was performed with aluminum oxide airborne-particle abrasion (50 μm Al_2O_3, <0.2 MPa, 5.0 cm from the framework) and steam cleaned. For veneering, a dedicated porcelain was used (CZR, Noritake), with coefficient of thermal expansion (CTE) (25–500°C) of $9.1*10^{-6}\,K^{-1}$, similar to Y-TZP, CTE (25–500°C) of $10.4*10^{-6}\,K^{-1}$, using established veneering techniques. Pink porcelain (Tissue Porcelain CZR, Noritake) was used where applicable, based on the provisional restoration, the volume of missing hard and soft tissues, and teeth length (Figures 3 and 4). Zirconia frameworks were fired in a calibrated porcelain oven (Programat EP 5000/G2; Ivoclar Vivadent s.r.l., Naturno, Italy) with a customized baking schedule to overcome the thermal stress on the veneering porcelain due to the low thermal diffusivity of Y-TZP (approximately 3 Wm/K), which

Figure 3 Silicone index to check an adequate support of the veneering material.

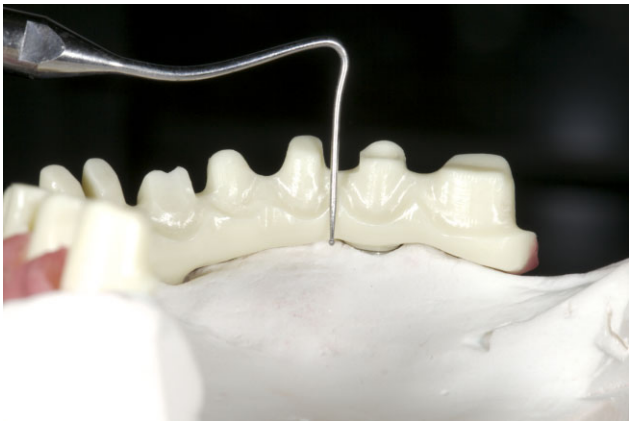

Figure 2 Prosthetic framework calix-shape design to ensure the minimum thickness of the connectors recommended by the manufacturer.

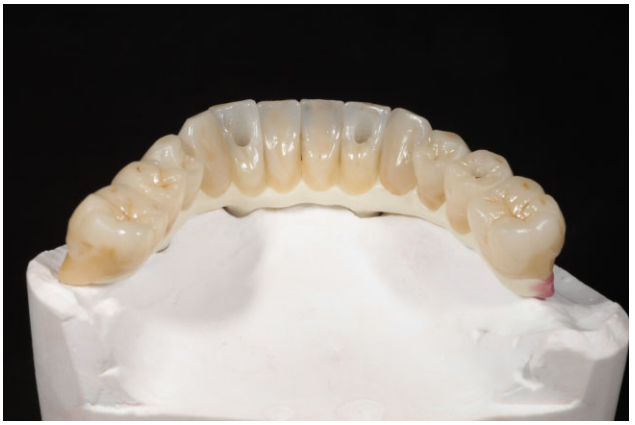

Figure 4 Pink porcelain was used where applicable, based on the volume of missing hard and soft tissues and the length of the teeth.

affects the cooling rate of the veneering porcelain.[42] The firing temperature was set at 900 to 910°C for the wash-bake, thus 90 to 100°C over the recommended temperature. Therefore, the two subsequent baking procedures were conducted at 810°C and 805°C, respectively. The heat rise rate was set for all baking procedures at 45°C degrees/minute to overcome the poor heat conductivity of the zirconia framework with a slow-rising temperature. The cooling phase was extended up to 10 minutes in order to achieve a slow cooling of the veneering porcelain and zirconia framework. All restorations were assessed by a prosthodontist for design, marginal fit, and surface finish.

Four to six months after implant placement, the definitive SCAZIR was inserted. Occlusion was adjusted and screws were tightened according to manufacturer instructions (35 Ncm). Screw access holes were acid-etched with a 9.8% hydrofluoric acid for 2 minutes and rinsed and cleaned with isopropanol. Then, the screw head was isolated with polytetrafluorethylene tape. The zirconium-ceramic surface of the screw access hole was prepared with 10-methacryloyloxydecyl dihydrogen phosphate containing bonding/silane coupling agent mixture (Clearfil™ Ceramic Primer; Kuraray Europe GmbH, Frankfurt, Germany) and sealed with a dual-cure, radiopaque, two-component, core build-up material supplied in an automix delivery system (Clearfil DC Core Automix; Kuraray Europe GmbH). Mutually protected occlusion with anterior guidance or balanced occlusion were used in cases of opposing fixed prosthesis and complete removable denture, respectively. Fifteen days after prosthesis delivery, a final occlusal adjustment was performed, and a rigid, acrylic night-guard was delivered to protect the veneering porcelain from occasional parafunctional habits. Patients were recalled every 4 months for hygiene maintenance and annually for occlusal adjustment. Patients were also requested to consult the clinic immediately if complications occurred. The last visit was ≥36 months after prosthesis delivery (mean 42.3 months; range 36–60 months).

Study Outcome Parameters

The primary outcome measures, assessed 15 days after prosthesis delivery and then annually, were implant and prosthetic survival and success rates. The implant success and survival criteria used in this study were modifications of criteria suggested by Van Steenberghe.[43] A "successful implant" is an implant that: 1) does not cause allergic, toxic, or gross infectious reactions either locally or systematically; 2) offers anchorage to a functional prosthesis; 3) does not show any signs of fracture or bending; and 4) does not show any signs of radiolucency on an intraoral radiograph using a paralleling technique strictly perpendicular to the implant-bone interface. A surviving implant was defined as an implant remaining in the jaw and stable, even if all success criteria were not fulfilled, whereas a failed implant was an implant that had been removed.[43] Prosthesis success was evaluated using modified evaluation criteria suggested by the California Dental Association.[44] A "surviving prosthesis" is a prosthetic reconstruction that is stable and in good function.

The secondary outcomes, assessed at the 3-year follow-up examination, were patient satisfaction and soft tissue parameters around the implants (bleeding on probing, plaque index, and gingival index scores), as well as implant and prosthesis survival rates. Patients gave their overall satisfaction score regarding masticatory function and aesthetics of their zirconia-based restorations on a 100 mm visual analogue scale (VAS; 0 = maximal disagreeing or minimal experienced and 100 = maximal agreement or maximal experienced). An independent outcome assessor asked the following questions: 1) "Are you satisfied with the function of your implant-supported prosthesis?" and 2) "Are you satisfied with the aesthetic outcome of your implant-supported prosthesis?"

Bleeding on probing (BoP) was assessed using a plastic periodontal probe (Plast-o-Probe; Dentsply Maillefer, Ballaigues, Switzerland) at four sites around each implant (mesial, distal, buccal, and lingual) according to the Mombelli Index[45] and reported a bridge level. Plaque score (PS) and gingival index (GI) were assessed at the abutment/restoration complex. PS, defined as the presence of plaque (yes/no), was scored by running a periodontal probe (PCP15; Hu-Friedy, Chicago, IL, USA) around the implant, parallel to the abutment surfaces, and calculated in percent on the basis of the total measurement points. GI was defined as follow: 0 = normal gingiva; 1 = mild inflammation, slight change in color, slighter edema, no BoP; 2 = moderate inflammation, redness, edema, and glazing, BoP; 3 = severe inflammation, marked redness and edema, ulceration, tendency to spontaneous bleeding. Two independent observers examined each patient.

Statistics

Descriptive analysis was performed using mean and standard deviation. Fisher's exact test assessed potential effects of main variables (implant placement timing after tooth extraction, prosthetic interface type, supporting implant number, arch type, and cantilever) on the prosthesis success rate. The rationale for choosing the Fisher's exact test is its appropriateness for small sample sizes of categorical variables. The null hypotheses were that the clinical outcomes of SCAZIRs would not be influenced by the aforementioned variables. Statistical analysis was carried out with the SPSS version 16.0 statistical package (SPSS Inc., Chicago, IL, USA).

RESULTS

No implants were lost, and all prostheses were in situ at the time of examination, accounting for a cumulative implant and prosthesis survival rate of 100% up to 5 years after insertion (Figure 5). All SCAZIRs were structurally intact, but chip-off fractures of the porcelain veneer occurred in 3/26 restorations, scoring a cumulative prosthetic success rate of 89%. No prosthesis replacements were necessary. From the dental unit perspective, 5/348 dental units experienced veneering material chipping, yielding a cumulative prosthetic success rate of 99% at the unit level. Two of the chip-off fractures were within the veneering ceramic and classified as "Sierra."[44] A thin layer of ceramic still remained on the zirconia framework, defining it as a cohesive fracture.[19] The remaining three events were classified as "Tango"[44] and judged as "adhesive" due to exposure of the core material.[19] The cohesive fractures were on the vestibular surface of the left mandibular first and second molar and were polished intraorally (Dialite; Brasseler USA, Savannah, GA, USA) without requiring any additional treatment due to their small size. One of the three adhesive chip-off fracture occurred on the lingual surface of a left second maxillary molar in the same patient, on the same side where the cohesive fractures occurred. The remaining two adhesive fractures both occurred in a second patient and were localized on the vestibular surfaces of the right mandibular first and second molars. The three adhesive chip-off fractures affecting the functional areas of the occlusal surfaces were restored with a porcelain laminate. No fracture of the zirconia frameworks and no other mechanical complications such as screw loosening or fracture occurred during the entire follow-up period (Figure 6).

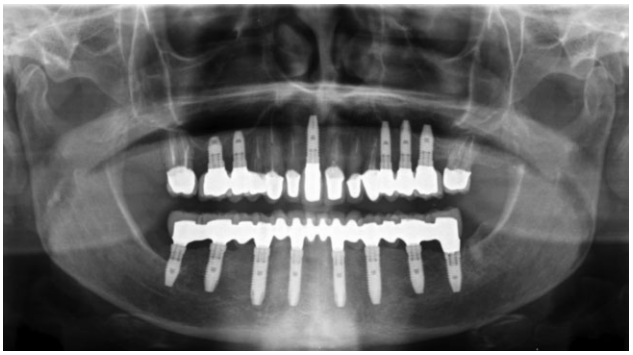

Figure 5 Ortopantomograph at 5-year follow-up of a cross-arch zirconium rehabilitation in the mandible.

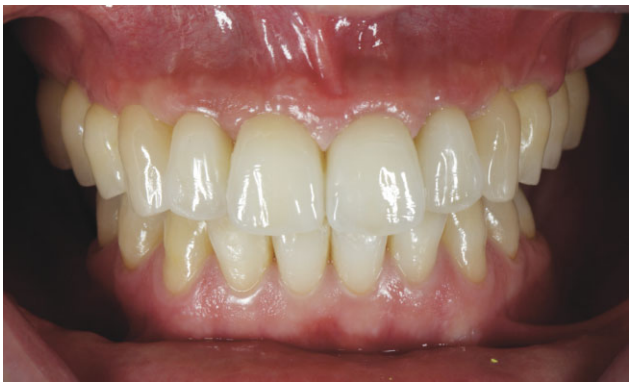

Figure 6 Definitive cross-arch zirconia framework with veneering ceramic at 5-year follow-up.

The VAS results revealed that all participants were functionally and aesthetically satisfied with their prosthesis. The average VAS score was 99.2 (SD 2.1; range 95–100) for function, and 98.1 (SD 2.9; range 90–100) for aesthetics.

BoP was reported on nine implant/abutment complexes of three SCAZIRs (12%). The cumulative plaque score was 1%. The GI was reported as 93% with normal gingiva, 2% with mild inflammation, and 5% with moderate inflammation.

Fisher's exact test revealed no effect of the timing of implant placement, arch type, presence of cantilever, or number of supporting implants. The only significant variable was the implant connection type, with veneering fractures only observed in patients restored with external connection implants ($p = .041$).

DISCUSSION

This study retrospectively evaluated implant and prosthetic survival rates and prosthetic success of

implant-supported, screw-retained, cross-arch, zirconia-based restorations over several years of follow-up. The limitations of this study are its retrospective nature and the limited number of participants. Nevertheless, 26 cross-arch zirconia implant bridges were placed in 22 patients and followed for ≥3 years, providing important new insights. This investigation was designed as a proof-of-concept pilot study to future multicenter randomized controlled trials (RCTs) with sample size calculation.

The null hypothesis that the five variables studied (implant placement timing, arch type, bridge span, number of supporting implants, and implant connection type) would not affect clinical outcomes was partially rejected. The only significant variable found was the implant connection type, with veneering fractures only observed in patients restored with external connection implants ($p = .041$). This statistical result will require confirmation in future RCTs involving a larger cohort.

No implant or zirconium framework fractures were experienced, resulting in overall implant and prosthetic survival rates of 100% up to 5 years. Furthermore, the overall 89% prosthesis success level and 99% at the unit level compared favorably with previous results studying cement[27] and screw-retained restorations.[23,27] No prosthesis replacements were required, and no mechanical complications (screw loosening or fracture) occurred during the follow-up. Another recent retrospective case series[23] concluded that CAD/CAM zirconia-based, implant-supported FDPs are a viable prosthetic treatment after 2 to 4 years on function. Similarly, a recent prospective clinical study on zirconia-based, implant-supported, cross-arch restorations[27] reported no fractures of the zirconium oxide frameworks after 3 years on function, resulting in high patient satisfaction. Thus, the ongoing development of new clinical and laboratory procedures have yielded successful results of the PFZ compared to PFM.[8]

Chipping of the veneering porcelain is a frequent drawback of zirconia-based restorations on teeth[2,8,32] and implants[23,27] and sometimes cannot be solved by porcelain polishing.[23–26] In the present study, only five chip-off fractures were reported at the unit level in 2/22 patients (i.e., 3/26 restorations) and were either polished or restored with a porcelain laminate. Four chip-off fractures occurred in the mandible, and all occurred on external hexagon connection implants. Patients wore rigid acrylic night-guards to prevent ceramic fracture related to occasional parafunctional habits. Nevertheless, a long-term maintenance regimen was useful for adjusting occlusal contacts to adjust for modified mandibular dynamics following neuromuscular adaptations over time. No correlations were observed between chip-off fractures and implant placement timing (immediate vs delayed), the number of supporting implants (<5 vs >5 implants), and presence of cantilever versus fully supported restorations.

Framework design, grinding the zirconium oxide after sintering, assuring bond strength at the veneering interface, and the porcelain mechanical properties and handling are advocated to minimize veneering fracture rate.[2,8,32] Nevertheless, no consensus guidelines have yet been developed to reduce fractures.[27,46]

The veneering ceramic is markedly weaker (flexural strength 92.7 MPa) than the zirconium oxide framework (1120 MPa) and is more prone to failure under complex tensile forces. When the core properly supports the veneering ceramic, the overall performance of the zirconia restoration improves and results in a lower chipping rate.[47–49] Our zirconia frameworks were anatomically designed with a cross-section calyx shape, a 120° chamfer preparation, and a shoulder width of 1 to 1.2 mm, to withstand mechanical loading stresses and ensure a functional customized veneering material thickness ranging between 1.5 and 2.5 mm.

Zirconia's strength is influenced by different surface treatments that produce different degrees and types of surface damage.[49,50] Surface flaws act as stress concentrating sites, leading to crack formation that decreases veneering material strength.[42] Surface micro-cracks may be induced by framework grinding of the sintered zirconia. Precision CAD/CAM milling procedures are advocated to deliver a customized zirconia framework requiring reduced postsintering reshaping and surface flaw development. We conditioned zirconia framework surfaces with 50 μm Al_2O_3 particle abrasion and steam cleaning. Framework abrasion is crucial for increasing the interfacial bond strength of the veneering material[51,52] by removing weakly attached surface grains and milling and grinding trace lines,[53,54] thereby minimizing adhesive fracture occurrences.[46] Contrarily, using larger Al_2O_3 particles (e.g., 120 μm) appears to result in significant weakening of the zirconia framework due to increased surface roughness.[55]

Liner applications may double the bond strength if proper contact is established between the veneering

ceramic and zirconia surface;[56,57] otherwise liners do not enhance shear strength.[58] Poor wetting causes micro-spaces between zirconia and the liner causing failures.[58] Regeneration firing of the zirconium framework for 15 minutes at 1000°C adversely affects shear strength[58] because even if the phase transition from monoclinic to tetragonal occurs at temperatures above 900°C,[5] the micro-cracks cannot be closed in such short time, thus decreasing the zirconia strength.[55,59]

Many variables affect the zirconia core-veneer bond strength, such as the core surface finish, mismatch between material CTEs, and the veneer wetting properties and volumetric shrinkage.[57] Commercially available zirconium oxide, core-veneer, all-ceramic systems have a shear bond strength ranging between 22 and 41 MPa.[60–62] Nevertheless, high chipping rates of veneering porcelain may be due to the raising of tensile stress within the porcelain at the interface because of CTE mismatch.[42] High residual thermal stress may lead to veneering material failure.[63] Thermal mismatch between the core material and the veneer porcelain is directly proportional to the magnitude of the residual tensile stresses within the veneer layer; therefore, closely matching the CTE is highly desirable. In the present study, the veneering of the frameworks was performed with a dedicated porcelain (CZR, Noritake), with the CTE (25–500°C, $9.1*10^{-6}\,K^{-1}$) similar to the CTE of the Y-TZP (25–500°C, $10.4*10^{-6}\,K^{-1}$), using established veneering techniques. The low thermal diffusivity of Y-TZP may cause unfavorable temperature distribution during backing and cooling procedures, causing internal stresses within the veneer material and at the interface.[50] Accurate baking procedures that customize the firing phases and the cooling regimen of the veneering porcelain minimizes internal stresses.[49,57,61,62] In the present protocol, restoration veneering baking and cooling temperatures and rates of change were specially tailored to achieve a tight bond of the ceramic with the zirconia surface.

Zirconium oxide's high biocompatibility, low plaque surface adhesion, absence of mucosal discoloration, and aesthetic properties contributed to successful soft tissue integration and patient satisfaction. All participants were functionally (99%) and aesthetically (98%) satisfied with their zirconia implant bridges. White and shaded zirconia frameworks prevent bluish discoloration of peri-implant soft tissues and may be beneficial if soft tissue recession occurs in the long term.

Nonhygienic inaccessible restorations are significantly associated with implant loss and a high rate of peri-implantitis.[64–66] We customized the construction of our prostheses to allow easy hygienic access to the supporting implants to improve oral hygiene maintenance and reduce the risk of biological complications. In this study, two light smokers (12%) experienced BoP at only nine implant/abutment complexes of three SCAZIRs. The cumulative plaque score was extremely low, and the 93% of patients experienced no gingivitis throughout follow-up, and the remaining 2% and 5% of patients experienced respective mild and moderate gingivitis. Refraining from smoking and maintaining good oral hygiene reduces biological complications in the long term.[67] In our study, scheduling follow-up visits every 4 months undoubtedly improved patient compliance with hygiene recommendations.

In conclusion, CAD/CAM manufactured, screw-retained, full-arch, zirconium oxide implant restorations are a viable alternative to the PFM restorative options for rehabilitating the edentulous patient.

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