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Optimizing passive fit and esthetic results of screw-retained zirconia implant-supported fixed complete dentures designed and produced digitally

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ABSTRACT

Objective: We aimed to present a novel protocol for the complete digital design and production of screw-retained zirconia implant-supported fixed complete dentures (IFCDs) to achieve predictable esthetic results and an optimal passive fit.
Methods: The novel protocol consisted of the following: 1) three-dimensional acquisition of intraoral and facial scans; 2) construction of the virtual patient; 3) conception of the new smile using computer-assisted design (CAD) software for the provisional prosthesis following standardized esthetic criteria; 4) finishing of the interim polymethyl methacrylate prosthesis after surgery; 5) CAD design of the final prosthesis following the same standardized esthetic criteria used for the provisional one; 6) computer-aided manufacturing of the final monolithic zirconia prosthesis; and 7) bonding of the titanium abutments into the zirconia framework using a physical cast derived from a zirconia jig.
Results: This novel protocol is time-efficient, delegable, and effective in achieving predictable esthetic results and optimal passivity, which may reduce the fracture rate of the zirconia framework.
Conclusions: Monolithic zirconia IFCDs may be a reliable alternative, and a fully digital workflow can reduce operative time and improve standardization and deferability. This protocol enabled the achievement of optimal passive fit, thereby reducing the probability of framework fractures.
Statement of clinical relevance: This novel protocol offers a time-efficient workflow that improves esthetic outcomes and passive fit, potentially reducing the incidence of zirconia framework fractures. It enhances the reliability and standardization of implant-supported prostheses, contributing meaningfully to advancements in restorative dental practices.

1. Introduction

The long-term success of implant-supported fixed complete dental prostheses (IFCDs) as a treatment option for complete-arch rehabilitation has been well-documented [1–3]. Zirconia, as a restorative material, along with a fully digital workflows is gaining increasing popularity among clinicians for IFCD construction [4]. However, long-term scientific evidence supporting these methods remains limited and inconsistent [5–8]. Digital dentistry is transforming the field of dentistry, offering clinicians significant advantages in terms of precision, predictability, replicability, delegability, and time efficiency [9–12]. However, there is a lack of high-quality trials comparing the industrial advancements of available digital applications with clinicians' readiness to routinely adopt these new technologies. Passive fit management is a key limitation of IFCD digital production. During the medium-term-follow-up period, a range of technical complications were observed in several cohort studies, the majority of which correlated with a lack of passive fit, such as screw loosening, screw fracture, titanium abutment debonding, and framework fracture [13–16].

Recent systematic reviews have shown that intraoral scans (IOSs) may lack sufficient accuracy for complete-arch digital impressions in patients with implants. While most existing studies have investigated dental casts rather than real patients, numerous interfering factors affect the accuracy of IOSs when used in clinical cases [17–21]. Moreover,

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even under the hypothesis that IOS trueness and precision are optimal, preliminary results using intraoral photogrammetry suggest [22], both titanium and zirconia dental prosthesis frameworks can exhibit distortions by the end of the production process [23]. A precise physical backup cast is mandatory to check for precision and passive fit before delivery. Due to production process-derived distortions, a tolerance leeway must be provided in the framework's abutment slots. However, this increases the probability of abutment debonding, as a greater cement thickness is inversely correlated with tensile strength [24,25].

The risk of fracture and complications due to these technological limitations has led some authors to propose luting monolithic zirconia restorations to titanium bars to prevent framework fracture [26–28]. However, this solution increases cost, operative time, and complexity and also requires more prosthetic space. We hypothesized that a simpler, cost-effective protocol could optimize the passive fit of a monolithic zirconia prosthesis with a one-piece design.

We aimed to present a novel protocol for the fully digital design and production of monolithic zirconia IFCDs, overcoming the problem of passive fit. Rather than attempting to correct the inherent limitations of IOS precision and framework deformation, this protocol seeks to bypass these issues through an alternative approach.

2. Materials and methods

A clinical case involving a 56-year-old female patient with good systemic health was examined to exemplify the described protocol (Fig. 1). Under controlled periodontal conditions, the patient underwent complete bimaxillary complete arch implant rehabilitation. During the first surgery, performed under intravenous sedation, the compromised residual maxillary teeth were extracted. Four cylindrical 3.75 mm titanium implants with internal conical connections (Paralle CC, Nobel Biocare) were placed in the maxilla and immediately loaded following multi-unit abutment (MUA) connection. A digitally designed, removable mandibular temporary prosthesis was delivered, ensuring optimal occlusion with a screw-retained, fixed maxillary provisional prosthesis. Two weeks later, four 3.75 mm implants (Paralle CC, Nobel Biocare) were placed in the mandible under the similar conditions and immediately loaded after the MUA connection. Three months after the second surgery, fabrication of the final screw-retained zirconia prosthesis was constructed. Definitive prostheses were delivered to the patient after 4 weeks.

The workflow described in this clinical report is as follows: 1) IOS and facial scan (FS) three-dimensional (3D) data acquisition; 2) construction of a virtual patient; 3) conception of the new smile for the provisional prosthesis using a computer-assisted design (CAD) software; 4) postsurgical finishing of the interim polymethyl methacrylate (PMMA) prosthesis; 5) CAD design and computer-aided manufacturing (CAM) of the final monolithic zirconia prosthesis; and 6) bonding of the zirconia framework to the titanium abutments from a physical cast obtained by a zirconia jig, in which the abutments have been positioned intraorally by the dentist using a simple and delegable procedure.

2.1. D data acquisition

During the first appointment, the following data were acquired: Cone Beam Computed Tomography (CBCT) images; IOSs using TRIOS® 5 (3shape); and FSs in both resting position and maximum smile using Easy Face Scan® (RCO s.r.l), aided by dedicated coupling fork. If the patient had residual teeth, the scan included the entire master cast, the opposing arch, and a centric registration. In the case of edentulous patients, the existing complete removable denture was relined and scanned using the TRIOS system to generate a Standard Triangulation Language (STL) file that accurately reproduced the edentulous arches (Fig. 2). At the same appointment, patients completed a medical history questionnaire. For those scheduled for surgery under intravenous sedation, their general medical status was objectively evaluated 1 week prior to surgery through electrocardiograms and blood tests.

2.2. Construction of the virtual patient

Using CAD software (Rijeka®, Exocad), the IOS and FS data were aligned with the help of coupling fork, which was related to the maxilla using a polyvinyl siloxane material impression (Occlufast Rock®, Zhermack). All digital files required to construct the virtual patient were imported into CAD and necessary alignments were performed using common reference zones shared among datasets (Fig. 3).

2.3. Conception of the new smile for the provisional prosthesis using CAD software

Once the virtual patient has been constructed within the CAD software (Rijeka®, Exocad) and integrated into the virtual articulator module (Artex CR®, Amann Girrbach), the new dental arches were designed starting from a digital tooth library. The positioning of the virtual patient within the digital articulator was guided by facial reference points marked with a pencil by the clinician prior to the FS, specifically at the midpoint of the tragus and the inferior part of the ala of the nose. The esthetic parameters were determined in the following standardized manner:

- The incisal edges of the upper central incisors were positioned to protrude 2 mm below the upper lip at rest and were aligned with wet line of the lower lip in the buccopalatal direction.
- The midline was positioned equidistant from the labial commissures in the maximum smile.
- The frontal occlusal plane of the maxilla was positioned parallel to the bipupillary plane.
- The anteroposterior occlusal plane of the maxilla was aligned parallel to the Camper's plane.

All of this information, derived from FSs, was available to the dental technician, who could visualize and work directly on the patient's face during every phases of prosthesis design. The maxilla was prioritized in

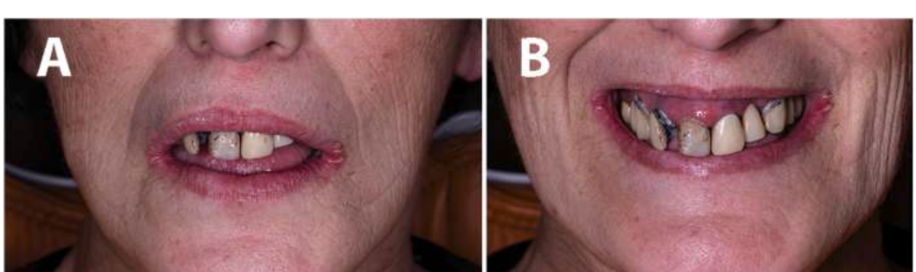

Fig. 1. Preoperative data acquisition: (A) The actual incisal edge exposure of the central incisors is evaluated at rest position prescribing the new position to obtain a 2 mm exposure. (B) Modifications of the midline are evaluated at the full smile position.

Fig. 2. Preoperative three-dimensional (3D) data acquisition: Intraoral scan (IOS) with TRIOS® 5 (3Shape Italy Srl, Milan, Italy). (A) Maxilla and mandible in occlusion; (B) In this case, the mandible is obtained from the scan of the old inferior mobile denture after relining with polyvinyl siloxane material; and (C) Inferior edentulous arch obtained by scanning the patient's previous complete removable denture.

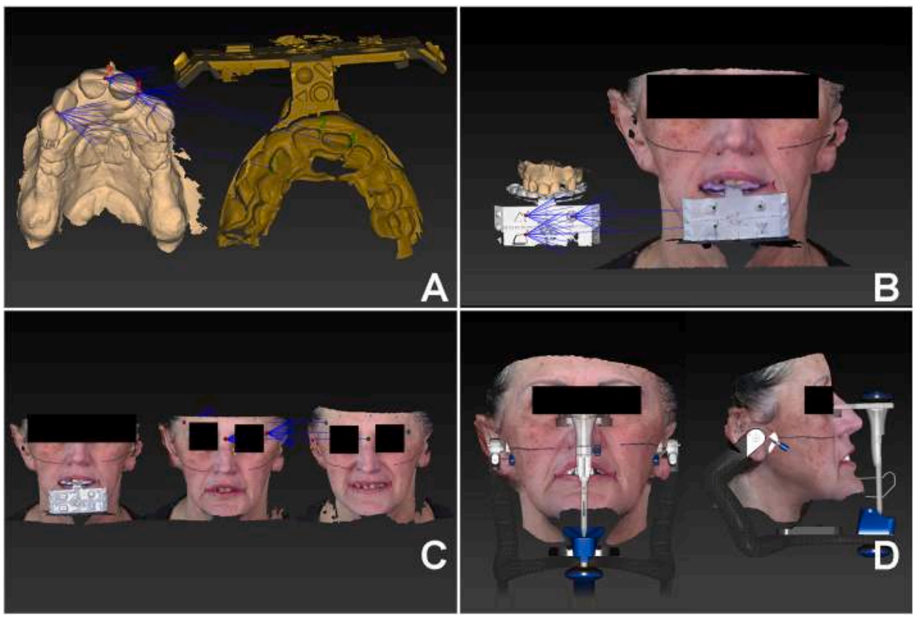

Fig. 3. Virtual patient construction: (A) Upper intraoral scan (IOS) and the fork are matched; (B) IOS and facial scan (FS) are matched using the fork; (C) The FSs with different smile exposures are matched; and (D) FSs are placed in the virtual articulator aligning the patient's Camper and bi-pupillary planes with the articulator horizontal plane.

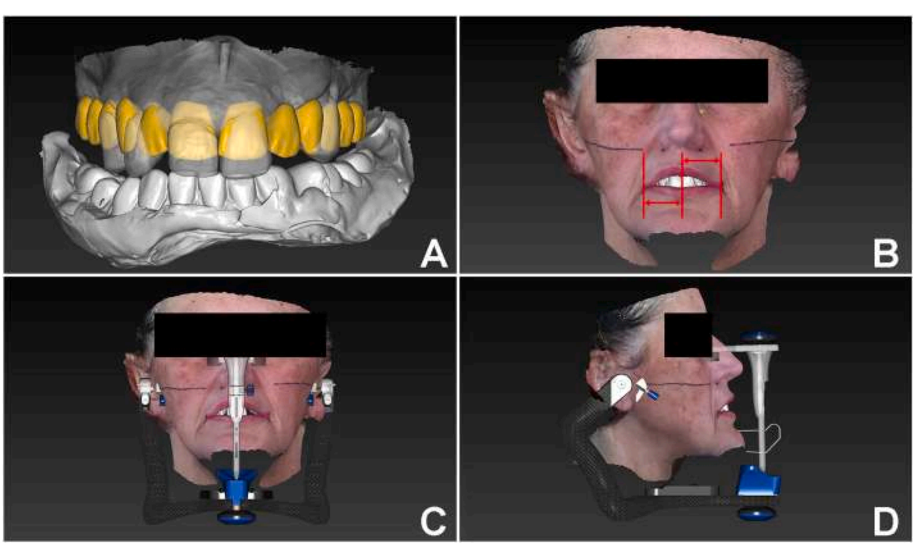

Fig. 4. Provisional prosthesis virtual design. Using a virtual dental arch, the maxilla is designed following the parameters listed: (A) The position of the incisal edge of the new maxillary central incisors is derived from the incisal edge of the old central incisors which were previously shortened to obtain exposure of 2 mm from the upper lip at rest position; (B) The midline is positioned equidistant from the labial commissures in the maximum smile; (C) The frontal occlusal plane of the maxilla is positioned parallel to the bipupillary plane; and (D) The anteroposterior occlusal plane of the maxilla is positioned parallel to the Camper's plane.

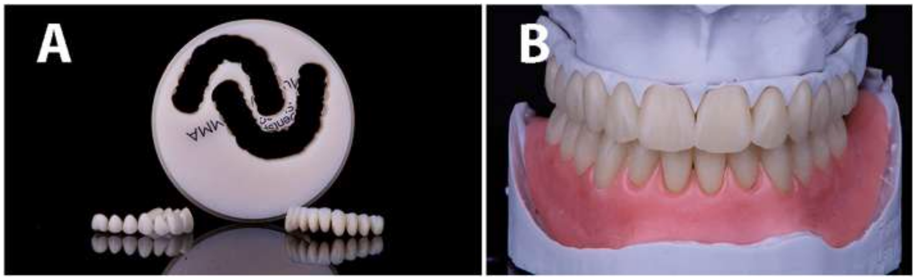

Fig. 5. Production and assembly of the interim prosthesis prototype.

the conception of new esthetics and functions (Fig. 4).

After designing the maxillary teeth according to esthetic parameters, teeth of the arch were positioned with standard occlusion under canine guidance. After setting the teeth, a support base for the arch was designed to transfer the centric relations and vertical dimensions as well as the position of the prosthetic interim teeth in relation to the final implant position. The base was glued to the dental arch. If only one arch was used, the dental set-up was adapted to the antagonist dental arch to meet the aforementioned criteria. The dental arches are milled (Wet & Dry M1®, ZIRKONZAHN) in PMMA (Temp Basic® A1, ZIRKONZAHN), while the bases of the prototype are printed (Key Model Ultralight® gray, Key Print). Subsequently, various components are assembled (Fig. 5).

2.4. Finishing of the interim PMMA prosthesis after surgery

After the placement of the implants, the prosthetic prototype was positioned relative to the implants using occlusion with the antagonist dental arch as a reference. In the reported case, a removable prosthesis was stabilized by a polyvinyl siloxane mask guided by the anatomical landmarks such as the hard palate and maxillary tuberosities or the retromolar pads during centric closure. The impression of the healing screws was obtained beneath the prototype using a fast-setting rigid polyvinyl siloxane material (Occlufast Rock®, Zhermack). Implant positions were then recorded using a plaster impression (Snow White®, Kerr) captured with customized impression tray. After the plaster cast was poured and had set, the healing screws were secured onto the analogs. Subsequently, the prototype was positioned and locked in place. A polyvinyl siloxane mask (Zetalabor®, Zhermack), was then fabricated to stabilize the prosthesis during the resin embedding phase (Fig. 6). Two anterior temporary abutments were welded to a 2 mm titanium bar extending across the entire length of the prosthesis. The two posterior cylinders were resin-bonded at the end to ensure proper passivation after resin embedding. The inferior part of the interim prosthesis had a convex profile and was maintained at an approximate 2 mm distance from soft tissues recorded in the impression. A screw-retained provisional fixed prosthesis could be delivered to the patient within 5 h. The standardization of this procedure ensures reproducibility and allows it to be delegated to personnel managing lower-complexity tasks.

In the reported clinical case, the same procedure was replicated in the mandible 2 weeks later.

2.5. CAD design and CAM of the final monolithic zirconia prosthesis

Three months postsurgery, the following IOS data were obtained (Fig. 7):

1) Maxilla with the screwed-on interim prosthesis.
2) Mandible with the screwed-on interim prosthesis.
3) Occlusion between the provisional prostheses.

Additionally, three new FSs with a fork, at rest, and during maximum smile were obtained. This was necessary because the lip support and soft tissue may have been modified compared to the beginning, affecting alignment accuracy.

The virtual patient was reconstructed in the wax-up module of the CAD software (Rijeka®, Exocad) and positioned in the virtual articulator tool. The definitive prostheses were designed according to the same esthetic and occlusal parameters established for the interim prostheses. Virtual patient positioning in the virtual articulator was guided using pencil marks made by the clinician before FS in the middle part of the tragus and inferior part of the ala of the nose. For the final tooth design, the interim teeth were considered as an esthetic reference point from which changes can be made (Fig. 8). The cantilever length was evaluated using the previously published parameters. The designs were milled in wax (Wax Disc; DENTSPLY SIRONA) and tested for fit and patient approval (Fig. 9). If needed, a second trial was scheduled following further adjustments. Upon final esthetic approval from both the clinician and the patient, the definitive prostheses were milled from a 1200 MPa multilayer zirconia disk (Thor, Orodent Srl) using a 5-axis milling machine (CORiTEC 350i Pro + loader, Imes-icore GmbH). After milling, the final prostheses were manually refined to correct detail loss caused by the milling procedures and were infiltrated to achieve optimal chromatic saturation and a lifelike 3D appearance (Zirconia Colouring Liquid, DMAX). Finally, the zirconia IFCDs were sintered, and the pink portion was layered, both according to the manufacturer's instructions.

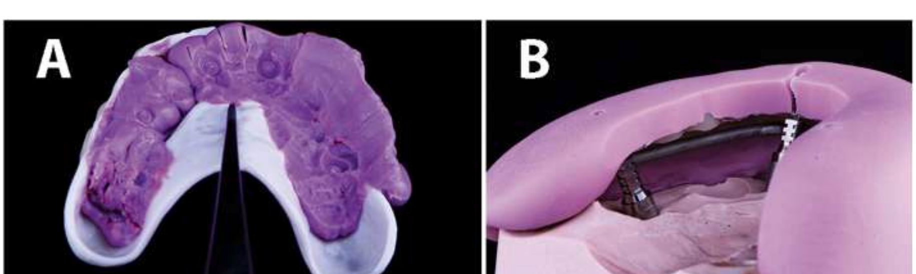

Fig. 6. Interim teeth position recording and production of the provisional prosthesis: (A) The impression of the healing screws is obtained beneath the prototype with a fast-setting rigid polyvinyl siloxane material (Occlufast Rock®, Zhermack); (B) A polyvinyl siloxane mask is then constructed (Zetalabor®, Zhermack) which will stabilize the prosthesis during the resin embedding phase; the two anterior temporary abutments are welded to a 2 mm titanium bar that extends for the entire length of the prosthesis.

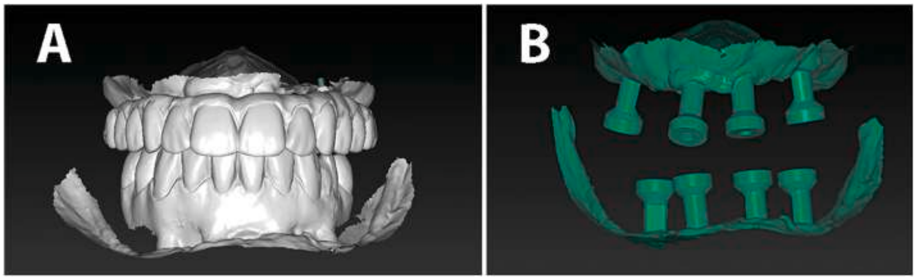

Fig. 7. Three-dimensional data acquisition for the final prosthesis construction: intraoral scan (IOS) with TRIOS® 5 (3Shape Italy SRL, Milan, Italy). (A) Maxilla and mandible with the provisional prostheses; (B) Maxilla and mandible with the scanbodies.

2.6. Bonding of the zirconia framework to titanium abutments using a physical cast obtained from a zirconia jig

During the esthetic try-in appointment for each arch, four definitive titanium abutments (Y-AVV-TCA, Sweden & Martina) were tightened to 15 Ncm on the multiunit abutments. These were then bonded together using a self-curing resin (Pattern Resin LC, GC America Inc.) in a zirconia jig previously prepared based on the STL cast. Therefore, the reciprocal positions in the mouth were fixed and transferred to the laboratory.

A master plaster cast was obtained by screwing analogs onto the titanium abutments at a torque of 15 Ncm. Titanium abutments were secured to the analogs and directly cemented into a definitive prosthetic framework. Vertical and horizontal microgrooves were provided by the manufacturer for patterned resin and cement retention on the titanium abutment surface, whereas horizontal grooves were made by a dental technician in the zirconia slots. After burning off the resin, the titanium abutments were cleaned and bonded using Universal Bond II, Tokuyama Dental (Fig. 10). After sandblasting, the inner surfaces of the zirconia framework slots were also bonded with Universal Bond II, Tokuyama Dental and the titanium abutments were cemented with a two-pack, low-contraction-rate resin cement (ESTECEM II *PLUS*, Tokuyama Dental). This process preserved the exact intraoral spatial relationship of the titanium abutments—when torqued to 15 Ncm on the MUAs—which was accurately transferred first to the gypsum cast and then to the final prosthesis. Owing to the production tolerance offsets of the MUAs, analogs, and titanium bases, loosening and retightening them could lead to different and unpredictable reciprocal positions inside the prosthesis without an optimal passive fit.

An 80 μm tolerance offset was provided in the zirconia slots for the titanium abutments. This allowed the accommodation of an insertion axis between the MUAs, without compromising the cement tensile strength despite some disparallelism.

One month after the final IOS, the definitive screw-retained fixed prostheses were delivered to the patient (Fig. 11).

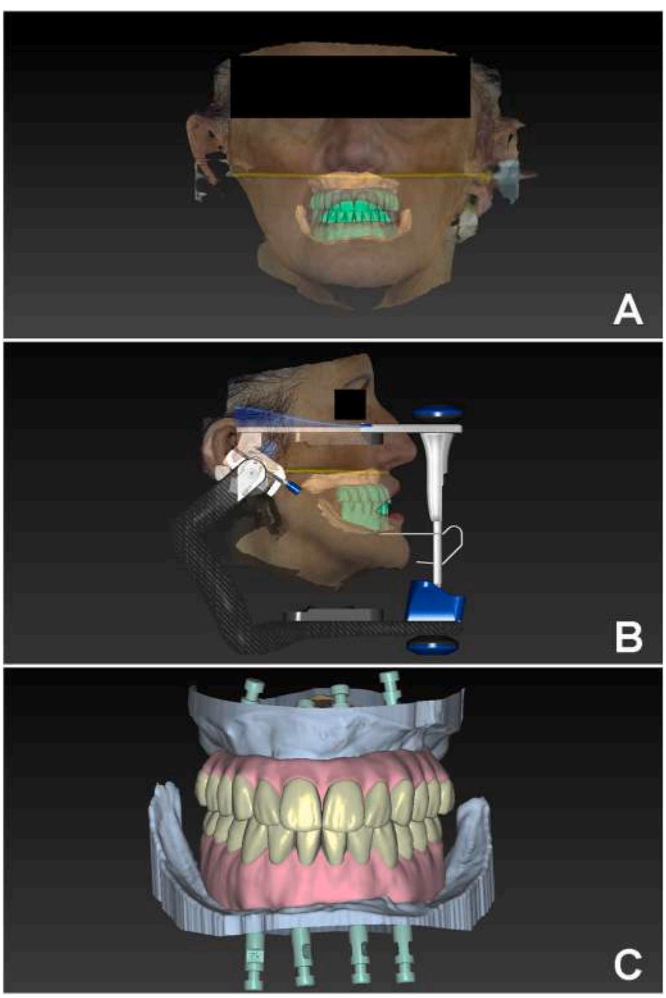

Fig. 8. Final prostheses are designed following the same criteria as the interim ones: (A) The frontal occlusal plane of the maxilla is positioned parallel to the bipupillary plane; (B) The anteroposterior occlusal plane of the maxilla is positioned parallel to the Camper's plane; and (C) Final design.

3. Results

Following this fully digital experimental clinical protocol, zirconia IFCDs for edentulous patients were designed to achieve an optimal passive fit and predictable esthetic outcomes. Such a fit is crucial for prosthetic rehabilitation, as it helps to prevent framework fractures.

This protocol was time-efficient. The entire process for single-arch rehabilitation, including surgery, required <3–3.5 h of patient chair time from the first appointment to final delivery. All prosthetic steps were simple, standardized, and non-skill sensitive. This resulted in a highly delegable procedure and reduced the probability of human error. The proposed approach to esthetic design for setting up teeth inside the FS of the patient was standardized, enabling dental technicians to obtain satisfactory and predictable esthetic results based on a definite and transferable protocol.

4. Discussion

New digital technologies have led to disruptive transformations in implant dentistry [9–12]. In recent years, most scientific research on this topic has focused on guided and navigational implant surgeries [29–31]. However, a less-explored but equally important application, particularly when considering financial implications-lies in prosthetic restorations [32]. The fully digital protocol described in this clinical report address this aspect offering clinicians a standardized, time- and cost-efficient, and highly delegable workflow for designing and producing screw-retained zirconia IFCDs. This protocol is applicable to all patients-partially or totally edentulous- who require complete arch implant

Fig. 9. Try-in of the milled prototypes of the final prostheses: (A) Prototypes in occlusion; (B) Full smile in frontal view; and (C) Full smile in lateral view.

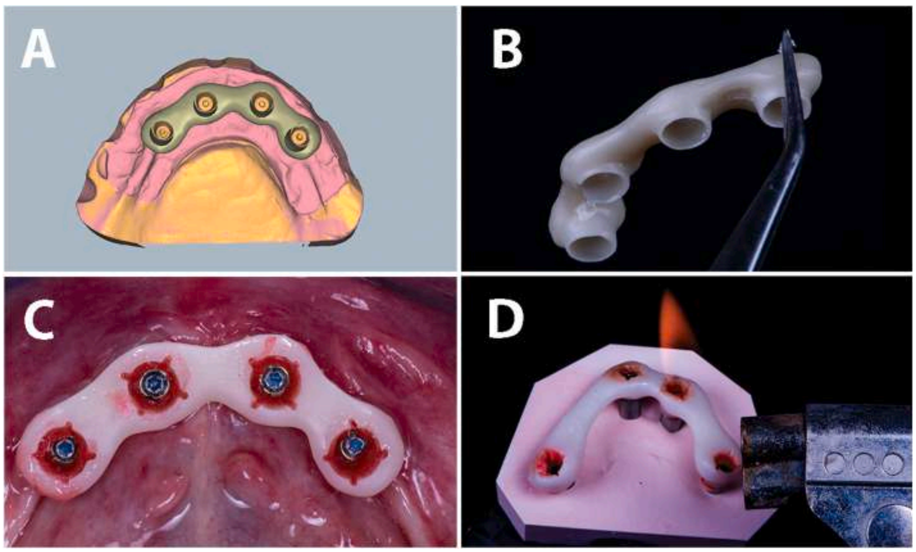

Fig. 10. Zirconia jig: (A) The zirconia jig is digitally designed on the STL cast; (B) The zirconia jig after sintering; and (C) titanium abutments are bonded with self-curing resin (Pattern Resin LC, GC America Inc.) in the zirconia jig; (D) The resin is burnt.

rehabilitation. Exceptions include patients who lack both residual teeth and prior removable prostheses, as there are no reference points for initiating esthetic analysis, and those in whom bone quantity or quality does not allow immediate loading of the implants. The protocol is centered around three key factors: first, the use of four standardized esthetic parameters eliminated subjectivity and operator-dependent factors to achieve the final esthetic result; second, the integration of FS technology allowed dental technicians to directly apply the four aforementioned parameters to a virtual patient using CAD software; and finally, the reciprocal position of the titanium abutments was accurately transferred from the patient's mouth to the zirconia framework using the zirconia jig technique.

In this protocol, the connection between the MUAs screwed onto the implants and monolithic zirconia IFCDs was obtained via titanium abutments bonded into specifically milled slots in the zirconia framework. To achieve an optimal passive fit, the titanium abutments must be bonded in the perfect position. However, both the IOS procedure and computer-assisted framework production are prone to distortions [17–23]. Therefore, tolerance space must be incorporated into the titanium abutment slots to allow their accommodation despite production distortions. As a result, titanium abutments cannot be bonded directly into the framework without the guidance of a physical cast, since their positioning would otherwise be variable and unpredictable. Although, printed casts have proven for creating guided surgery templates [33]; however, their accuracy in prosthetic use in implant cases has been investigated with inconsistent results [34]. Moreover, studies assessing printed cast accuracy have mostly analyzed dentate casts and compared them to digital references, rather than verifying against a patient's actual oral anatomy, thus overlooking the additive errors introduced by analog accommodations in the cast. [33–35]. In our opinion, printed casts with analogs are not sufficiently accurate for use in titanium abutment bonding. The core principle of our protocol is to replicate the exact spatial relationship of the titanium abutments-once tightened at final torque-within the zirconia framework, through a simple, predictable, and delegable technique. In the present protocol, titanium abutments were screwed onto the MUAs, tightened, and bonded to a zirconia jig using a low-expansion-rate resin. They maintained the reciprocal positions in the zirconia jigs. The MUA analogs

Fig. 11. Final prostheses: (A) Final zirconia implant-supported fixed complete dental prostheses (IFCDs) in occlusion; (B) Rest position; and (C) Full smile.

were then tightened to the titanium abutments and immersed in low-expansion rate gypsum. Titanium abutments were not unscrewed from this gypsum cast until they were bonded to the final zirconia framework. Before the final cementation, the zirconia jig was removed by burning the resin, and the titanium abutments were cleaned while remaining screwed onto the cast. Thus, to obtain an optimal passive fit, the reciprocal position in the final framework was the same as that in the mouth. The main limitation of this protocol is the management of cases in which the final alignment of the MUAs does not allow the fitting of the framework on titanium abutments without unscrewing them. In the latter, a single abutment is removed from the cast and directly bonded intraorally by a clinician. The best way to overcome this limitation is to surgically optimize the alignment of the MUAs. Additionally, if the, MUAs are deeply embedded within the gingival tissue, the pattern resin linkage may be insufficient to stabilize the titanium abutment within the zirconia gig. In such situations, a thin layer of resin may be prepolymerized over the titanium abutment surface before it is screwed onto the MUA. This enhances retention despite the presence of trans-mucosal moisture.

5. Conclusions

In this clinical report, we presented a reliable, time-efficient, and highly delegable protocol for the digital production of monolithic zirconia IFCDs. In this protocol, the esthetic was achieved through a standardized approach that excludes the operator's subjective evaluations, ensuring consistent and predictable result regardless of the clinician's or dental technician's skill level. The innovative use of zirconia jig strategy enabled optimal passive fit, further enhancing the reproducibility of the protocol. Appropriately designed clinical studies with larger sample sizes are needed to validate these findings.

CRediT authorship contribution statement

Federico Tirone: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Stefano Salzano:** Project administration, Methodology, Investigation. **Erik Rolando:** Validation, Supervision, Methodology, Investigation, Conceptualization. **Dan Andrei Pirja:** Supervision, Software, Methodology, Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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