Expert Consensus on Clinical Application for Digital Full-contour High-translucent/Ultra-translucent Zirconia Restorations

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This expert consensus addressed the use of digital full-contour high-translucent/ultra-translucent (HT/UT) zirconia restorations. HT/UT zirconia, stabilised with 4 mol% to 6 mol% yttria, balances flexural strength (550 to 1100 MPa) and enhanced translucency (45% to 55% light transmission) through a cubic-tetragonal microstructure while maintaining excellent biocompatibility and aging resistance. Clinical applications include single crowns, short-span bridges, veneers (0.3 to 1.0 mm) and implant-supported prostheses (screw-/cement-retained with specific thickness requirements). The digital workflow involves precise preparation, digital impressions, computer-aided design, milling, sintering and post-processing (surface polishing to Ra ≤ 0.25 µm). A lack of unified standards causes variable practices in the clinic. This consensus provides guidelines to standardise procedures, promoting predictable quality and long-term success of HT/UT zirconia restorations.

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Digital full-contour restoration consists of a single-layer material without a veneering structure, created using CAD/CAM technology. Notably, the light transmittance of traditional zirconia ceramics, such as 3 mol% yttria-stabilised tetragonal zirconia polycrystal (3Y-TZP), is not ideal, and traditional zirconia can only be used as the substrate for crown and bridge restorations. To enhance aesthetics, previous restoration techniques involved applying veneering porcelain; however, several studies have shown that zirconia restorations with veneering porcelain frequently chip on the surface, compromising long-term stability of the restorations.[1-5] Advancements in dental material technology have led to the development of new high-translucent and ultra-translucent (HT/UT) zirconia, characterised by improved optical properties.[6-8] This material enables the fabrication of full-contour restorations, which include fixed restoration types such as full crowns,[9] fixed partial dentures and veneers.[10-13] Only staining and glazing are necessary to meet clinical aesthetic standards, reducing the risk of mechanical issues. Additionally, digital full-contour zirconia restorations can precisely represent the planned design and the digital files can be archived, allowing exact duplication for future use.

Despite these advancements, there is currently no unified standard for the clinical use of digital full-contour HT/UT zirconia restorations, including aesthetic and restoration structural design, process technology and key considerations in grinding and polishing. Variations in design and manufacturing procedures among institutions have resulted in a lack of standardised treatment guidelines and consistent quality control measures in the field. Consequently, due to the non-uniform design and operation methods, the long-term success of these restorations remains uncertain. This expert consensus is based on numerous research findings and synthesises current evidence, offering guidelines for clinicians and technicians on designing and fabricating full-contour HT/UT zirconia restorations to standardise clinical practice.

Characteristics of HT/UT zirconia restoration materials

Material composition

HT/UT zirconia typically includes a yttria stabiliser in the range of 4 mol% to 6 mol%. This specific composition allows for easy abbreviations like 4Y-PSZ, 5Y-PSZ, and 6Y-PSZ, where the number indicates the molar percentage of yttria and PSZ stands for partially stabilised zirconia. Unlike traditional zirconia formulations, these advanced materials are engineered to balance mechanical strength with optical transparency, making them well-suited for applications that demand both strength and aesthetic appeal.

Zirconia exhibits polymorphic behaviour, manifesting in three distinct crystal structures that are temperature dependent. At room temperature, the stable phase is monoclinic (m-ZrO_2), characterised by a slightly distorted crystal lattice. Upon heating above approximately 1170°C, a phase transition to the tetragonal structure (t-ZrO_2) occurs, which features higher symmetry and greater structural uniformity. Further heating beyond approximately 2370°C results in a transition to the cubic phase (c-ZrO_2), the most symmetrical and thermodynamically stable form at high temperatures. This phase transformation behaviour is crucial for understanding the material's properties and processing requirements.[6-8,14]

Traditional zirconia materials, such as 3Y-TZP (3 mol% yttria-stabilised tetragonal zirconia polycrystals), primarily consist of the tetragonal phase. The inclusion of yttria stabiliser in these materials suppresses the monoclinic-to-tetragonal phase transition, maintaining the tetragonal structure at room temperature and enabling the material to demonstrate remarkable fracture toughness through a mechanism known as transformation toughening. In contrast, HT/UT zirconia materials also have a tetragonal-dominant crystal structure but differ in their stabiliser content and sintering protocols, incorporating a significant proportion (exceeding 20%) of cubic crystals into their microstruc-

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ture. This deliberate modification of the crystal phase composition plays a key role in improving translucency, as the cubic phase interacts differently with light, reducing scattering and enabling better light transmission through the ceramic matrix. Precise control of phase composition and microstructure is therefore critical to optimising both the mechanical strength and aesthetic appearance of these materials for applications such as dental prosthetics.[14-16]

Aesthetic effects

Colour

In HT/UT zirconia, colour versatility is achieved by adding rare-earth metal oxide dopants to the raw powder matrix during the pre-sintering stage.[17,18] This solid state doping mechanism utilises the chemical affinity between ZrO_2 and transition metal oxides, which may include rare earth elements. These dopants undergo solid solution formation during sintering (1300°C to 1500°C), dissolving into the tetragonal or cubic zirconia lattice and creating stable colour centres via charge compensation mechanisms.

Post-sintering colour customisation in HT/UT zirconia restorations is accomplished through a dual staining method, carefully tailored to the different processing stages of the prosthesis. For green-state (unsintered) machined zirconia blanks, internal staining is used, where pigment infiltrates the porous matrix through vacuum pressure or ultrasonic cavitation. This technique facilitates a penetration depth of approximately 50 to 100 μm, producing homogenous colouration that remains stable throughout the sintering-induced densification process, which typically involves 15% to 25% linear shrinkage.[19,20] Conversely, for fully sintered restorations, external staining is the preferred approach. This surface modification technique utilises low-melting glass-based pigments, which are thermally fused to the zirconia surface at temperatures ranging from 800°C to 950°C.[21-23] External staining excels at the micro-level customisation of anatomical features such as mamelons, perikymata and age-related discolouration, as the pigmentation adheres to the dense ceramic surface without compromising the material's inherent mechanical integrity.

Both staining protocols depend on spectrophotometric analysis to match colours against standardised shade guides (e.g., VITA Classical shade tabs [VITA Zahnfabrik, Bad Säckingen]) or patient-specific reference samples. This analytical approach ensures precise control of chroma, value and hue.

Translucency

The optical transmittance characteristics of HT/UT zirconia are significantly modulated by the concentration of yttria stabiliser. As a critical compositional parameter, the mole percentage of yttria exerts a discernible influence on the material's optical performance. For instance, 4Y-PSZ (4 mol% yttria-stabilised zirconia) demonstrates a visible light transmittance (400 to 700 nm) in the range of 45% to 47%, whereas 5Y-PSZ and 6Y-PSZ formulations exhibit elevated transmittance values spanning 48% to 55%.[24-26] These quantitative results are obtained from spectrophotometric analyses on polished 1-mm-thick specimens, using air and black backgrounds as reference standards to ensure accuracy and minimise systematic errors. The observed increase in transmittance with higher yttria content is attributed to the formation of a cubic-tetragonal phase composite structure. This microstructure effectively reduces light scattering by minimising phase boundary mismatches, thereby enhancing the overall optical transparency of the zirconia ceramics.

The light transmittance of these advanced zirconia ceramics depends on a complex interaction between material properties and processing parameters:

1. Material thickness: Translucency decreases exponentially with increasing thickness.[27-30] For 4Y-PSZ, a 1-mm specimen shows a 12% to 15% reduction in transmittance compared to 0.5 mm, while ultra-translucent 6Y-PSZ maintains higher transmittance due to its lower scattering coefficient.[27] Clinically, this requires optimising the thickness of dental restorations, where incisal edges (1.0 to 1.5 mm) may need pigmented layering to imitate natural dentin opacity, while the cervical region (0.5 to 0.7 mm) utilises inherent translucency for enamel-like aesthetics.
2. Material purity: The translucency of zirconia ceramics is correlated with the content of alumina (Al_2O_3) and other oxides.[31,32] Metal oxides used as dopants scatter incident and reflected light, and Al_2O_3 dopants negatively affect the translucency of zirconia ceramics.
3. Grain size: Grain size is determined by examining a transverse metallography mount under an optical microscope and counting the grains within a specific area. Within the visible light spectrum, larger grains improve translucency. Unlike $t\text{-}ZrO_2$ (200 to 300 nm), $c\text{-}ZrO_2$ has bigger grains (400 to 600 nm) and exhibits optical isotropy, both of which decrease light scattering and enhance translucency.[27,29] Larger grains reduce the number of grain boundaries, which are

key points for light scattering. Fewer grain boundaries lead to less light scattering loss at these interfaces.[29,33] The crystal structure of c-ZrO_2 guarantees consistent light speed in every direction, preventing birefringence-related light path irregularities. This reduces unnecessary light scattering, which further improves the material's translucency.

4. Density: Higher density of zirconia improves translucency. Pores in zirconia ceramic scatter light as it passes through.[27,29,33] When light hits these pores, its path changes, leading to less direct transmission and more scattering. This reduces the material's translucency, resulting in an opaquer appearance.
5. Sintering process: Different sintering conditions affect the porosity of zirconia ceramics.[34,35] Parameters like sintering temperature and holding time affect the material's compactness, which in turn influences porosity. Optimising sintering conditions can reduce porosity, minimise light scattering and improve translucency.

Mechanical properties of HT/UT zirconia

Flexural strength

The flexural strength of HT zirconia ranges from 650 to 1100 MPa, and that of UT zirconia ranges from 550 to 900 MPa.

Fracture toughness

The fracture toughness of HT zirconia ranges from 4 to 6 MPa·$m^{1}/^{2}$, and that of UT zirconia usually ranges from 3 to 4 MPa·$m^{1}/^{2}$.

Hardness

The Vickers hardness reaches over 1200 HV.

Compressive strength

The compressive strength of HT/UT zirconia typically ranges from 1000 to 2000 MPa or higher.

Aging performance

3Y-TZP obtains its remarkable mechanical properties (high strength, approximately 900 to 1200 MPa; fracture toughness, approximately 5 to 10 MPa·$m^{1}/^{2}$) through the tetragonal-to-monoclinic (t→m) phase transformation toughening mechanism. When a crack propagates, the metastable tetragonal grains near the crack tip transform into the monoclinic phase, accompanied by a ~3% to 5% volume expansion. This expansion generates compressive stresses that resist crack growth, improving toughness. However, the tetragonal phase is metastable and may spontaneously transform from the t to m phase under hydrothermal conditions, such as moisture, high temperature or prolonged exposure to body fluids in biomedical use. This is known as low-temperature degradation (LTD) or hydrothermal aging. The resulting monoclinic phase and volume expansion lead to microcracking, reduced strength and eventual failure over time.[25,36-43]

Increasing the yttria (Y_2O_3) content encourages the tetragonal-to-cubic phase transition. The cubic phase is thermodynamically stable and does not undergo t→m transformation. As a result, the proportion of metastable tetragonal grains is reduced, thereby enhancing translucency and hydrothermal aging resistance. The aging performance of HT/UT zirconia refers to its ability to maintain structural and functional stability under long-term environmental or mechanical stress.

Crystal phase stability

Following simulated aging processes, such as thermal cycling or mechanical loading, the crystal structure continues to be mainly tetragonal, with no change in the cubic phase content.[25]

Mechanical property retention

Key properties such as flexural strength, fracture toughness and Vickers hardness show no significant degradation.[25,36,37]

Translucency stability

The material maintains stable light transmittance and aesthetic qualities over time, ensuring consistent colour and optical properties in restorations in the long term.[38-43]

Chemical resistance

There is high stability within the oral environment, preventing degradation or ion release, which is essential for biocompatibility and long-term structural integrity.

However, increasing yttria content also decreases fracture toughness because the t→m toughening mechanism is less effective due to a reduced number of tetragonal grains.

Biocompatibility

HT/UT zirconia demonstrates exceptional biological safety and compatibility with tissues. This material is chemically inert, undergoing virtually no chemical reactions within the human body and releasing no harmful substances. Its superior corrosion resistance ensures long-term stability of both physical and chemical properties. Tissue compatibility refers to the material's ability to coexist with surrounding tissues without eliciting adverse effects (e.g., inflammation, fibrosis or immune responses).

Biocompatibility with tissues

HT/UT zirconia crowns or bridges contact the oral mucosa and saliva directly. Their inert properties prevent irritation, and they do not interact with saliva components, such as enzymes and minerals, avoiding harmful deposits or byproducts.

Implant abutments

Compatibility is essential for zirconia-based dental implant abutments that penetrate soft tissues and interface with bone. Studies show that zirconia surfaces support soft tissue attachment (direct bonding with epithelium and connective tissue) and do not trigger foreign body reactions or inflammation.[44-46]

Processing performance

Machinability

Because of zirconia ceramic's dense structure, high hardness and brittleness after sintering, processing HT/UT zirconia presents certain challenges. The primary current processing method is grinding before sintering, with its precision influenced by factors such as grinding strategies, equipment and tool performance. The space between the tissue surface of HT/UT zirconia restorations and the prepared tooth is under 120 µm.[35,47,48]

Marginal quality

HT/UT zirconia can be customised for different prepared tooth types to create restoration margins with precise shape and specific thickness, ensuring high-quality margins.[47,48]

Sintering

The sintering process is selected based on the restoration type, restoration thickness, material properties and sintering equipment. The standard sintering process takes 4 to 8 hours; however, certain HT/UT zirconia can be rapidly sintered using fast sintering equipment.[49,50] The rapid sintering time is generally 1 to 2 hours.[41,49-51]

Post-processing

After sintering, HT/UT zirconia requires post-processing steps, including grinding, polishing, staining and glazing. Clinical adjustment via grinding and polishing is necessary to enhance surface finish, achieve a smooth surface and ensure the surface roughness (Ra value) is ≤ 0.25 µm.[52-55]

Properties of HAT/UT zirconia restorations

Clinical indications for digital HT/UT zirconia full-contour restorations

HT/UT zirconia differs from traditional zirconia in both mechanical and aesthetic properties, so its clinical application is not entirely consistent with that of traditional zirconia.

Single crown

It can be used for single-tooth full crown restoration of both anterior and posterior teeth, and appropriate materials can be selected based on the aesthetic requirements for the colour and translucency of the restoration (Fig 1).

Fixed bridge

HT/UT zirconia with a flexural strength greater than 800 MPa can be used for three- or four-unit short-span fixed partial denture restorations in the anterior region and for three-unit fixed partial denture restorations in the posterior region.

Veneer

It can be used for both traditional (0.5 to 1.0 mm) (Fig 2) and ultra-thin (0.3 to 0.5 mm) veneer restorations (Fig 3).

Fig 1 HT/UT zirconia full-contour crown restoration for anterior teeth.

Fig 2 HT/UT zirconia traditional veneer restoration for tetracycline-stained teeth.

Fig 3 HT/UT zirconia ultra-thin veneer restoration for peg-shaped maxillary lateral incisors.

Single tooth implant superstructure restoration

1. Screw-retained one-piece crown: This can be used for implant crown restoration in both anterior and posterior regions, typically using a screw-retained approach. The use of a finished metal base is recommended to reduce the risk of interfacial fracture. The posterior region requires at least 5 mm vertical restoration space (Fig 4).
2. Cement-retained outer crown: This can be used for the outer crown of implant-supported cement-retained restoration in both the anterior and posterior regions. When the cement-retained method is adopted, the posterior region requires at least 6 mm vertical restoration space.

Three- or four-unit fixed partial denture supported by implants in the anterior tooth area

1. Screw retention: This can be used for screw-retained three- or four-unit fixed partial denture restorations supported by implants in the anterior region, requiring implants with good 3D implantation directions. The screw access points should be located on the lingual side, and there should be good parallelism between implants.
2. Cement retention: This can be used for the outer crown portion of cement-retained three- or four-unit fixed partial denture restorations supported by implants in the anterior region.

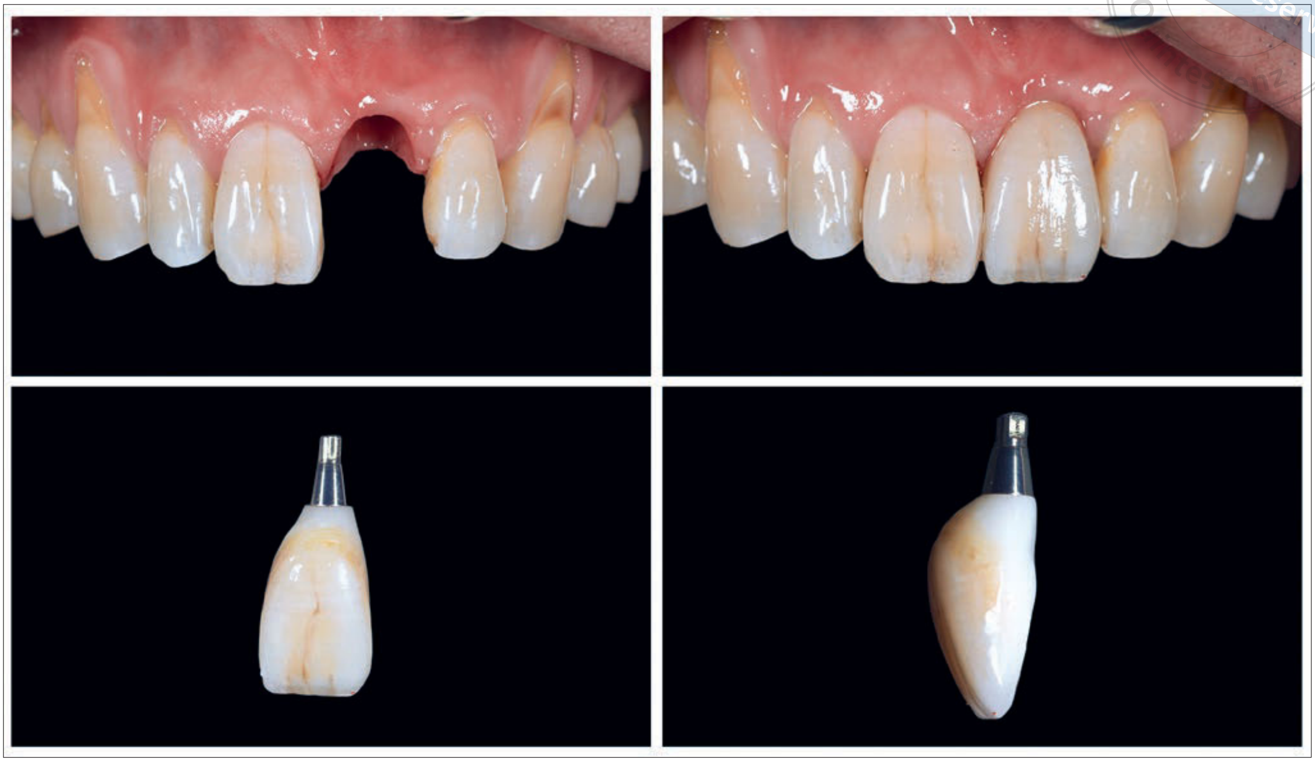

Fig 4 HT/UT zirconia full-contour crown restoration for screw-retained one-piece single crown.

Fixed restoration supported by implants in the edentulous arch

This can be used for the outer crown portion of fixed restorations supported by implants in edentulous arches (complete anodontia), applied over the implant-supported framework (Fig 5).

Aesthetic treatment of digital HT/UT zirconia full-contour restorations

The aesthetic features of the full-contour restoration primarily involve two steps: shade selection and staining.

Shade selection

Use a colour-matching plate compatible with HT/UT zirconia materials. Select adjacent natural teeth or the contralateral homonymous tooth for colour matching. Meanwhile, perform colour matching on the prepared tooth structure, and choose materials with suitable colour and translucency.

Staining

Before sintering, internal staining is applied to the zirconia blank's surface to pre-colour the restoration. After sintering, glaze and external stains are added to the surface of the sintered zirconia restoration to further refine its colour and translucency, achieving a more customised aesthetic final result.

Grinding and polishing of digital HT/UT full-contour restorations

Grinding can easily induce phase transformation in zirconia; therefore, grinding of HT/UT full-anatomy restorations should be kept to a minimum.[52,53] Using digital technology, the morphology of natural teeth can be accurately replicated when needed. When necessary, digital occlusal design should be employed to simulate both static and dynamic occlusion. Regarding cases with multiple restorations, it is recommended to fabricate temporary restorations first and duplicate the morphology of the temporary restorations after clinical adaptation.

After the clinical try-in and any necessary grinding, a comprehensive polishing process is essential to achieve

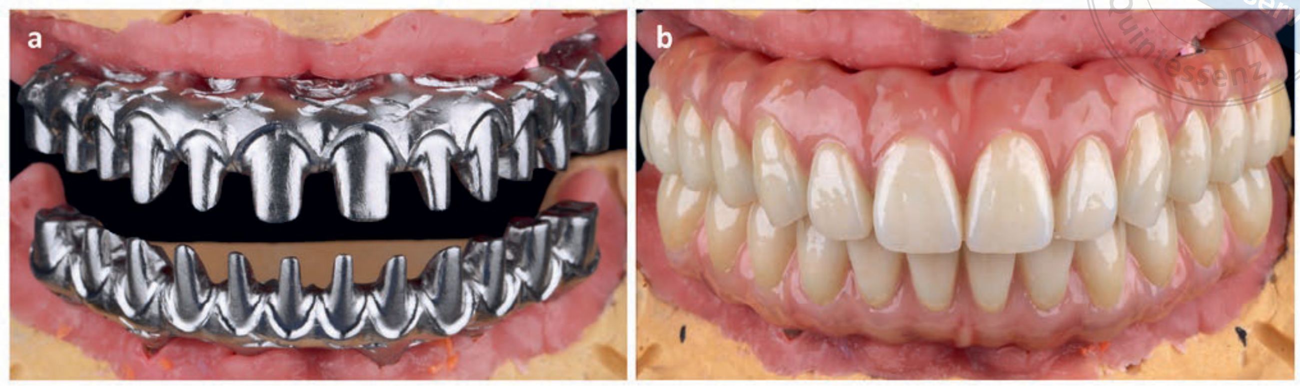

Fig 5a and b HT/UT zirconia used for the outer crown of a fixed restoration supported by implants in an edentulous arch. Titanium framework **(a)**. HT/UT zirconia full-contour crown and gingiva-coloured resin-based composites cemented on the framework **(b)**.

Table 1 Sequential polishing steps and tools.

Steps	Tool/materials	Function
Rough polishing	Rubber polishing wheel/ coarse polishing paste	Remove obvious scratches from grinding and initially smooth the surface
Medium polishing	Fine-grit polishing wheel/ polishing strips	Further refine the surface, reduce roughness and create preliminary gloss
Fine polishing	Wool wheel/ultra-fine polishing paste	Enhance surface finish to give the restoration a natural gloss similar to natural enamel
Glazing	Silicone rubber tip/ nano-level polishing agent	Perform detailed polishing on complex anatomical structures (e.g., fossa, proximal surfaces) to enhance translucency and light reflection

a smooth surface on the restoration. This helps ensure optimal mechanical properties and minimises wear on the opposing teeth.[52-55]

Grinding treatment

The purpose of clinical grinding is to:

- ensure normal occlusal relationships between the restoration and the abutment tooth, adjacent teeth and opposing teeth, free of premature contacts or interferences;
- adjust the anatomical morphology of the restoration (such as cusps, fossae and marginal ridges) to meet physiological, functional and aesthetic requirements;
- correct minor errors that may exist in the digital design or processing to ensure precise seating of the restoration.

The clinical grinding principle involves:

- Making incremental adjustments: Avoid excessive material removal in one step to prevent compromising the restoration's strength or aesthetics.
- Preserving anatomical structures: Prioritise grinding non-functional cusps, developmental grooves and other secondary structures while avoiding damage to critical structures, such as the connector of fixed partial denture and implant abutment. If critical structures need modification or significant occlusal interferences exist, it is necessary to return the restoration to the dental laboratory for adjustment or remanufacturing.
- Referencing natural tooth morphology: Use the contralateral homonymous tooth or adjacent teeth as a reference to ensure the restoration's morphology is harmonious and natural.

Polishing treatment

The process of polishing involves rough polishing, medium polishing, fine polishing and glazing (Table 1). The purpose of sequential polishing treatment of HT/UT zirconia full-contour restoration is to:

- achieve a smoother surface, as surface roughness affects the performance and service life of zirconia and polishing reduces bacterial adhesion and wear on opposing teeth;[56-58]
- enhance the restoration's translucency and gloss, making it closer to the optical properties of natural teeth (especially for HT/UT zirconia);[55,56]
- eliminate fine scratches generated during grinding to avoid stress concentration and potential fracture

of the restoration. Grinding easily causes phase transformation of zirconia, and proper polishing can remove the transformed layer and restore the material properties.

Clinical inspection after grinding and polishing treatment

Through systematic clinical inspection, digital full-contour restorations can achieve ideal occlusion, aesthetics and mechanical properties, enhancing patient satisfaction and long-term success rates.

1. Visual inspection: Observe the restoration's surface under strong light for smoothness, scratches and colour coordination with adjacent teeth.
2. Tactile inspection: Surface topography evaluation and surface roughness measurements can be performed in as-sintered specimens using a non-contact optical 3D surface measurement system. The Ra value of HT/UT zirconia restorations should be ≤ 0.25 µm, close to natural enamel (Ra ≈ 0.1 to 0.3 µm), to reduce plaque adhesion.[56-58]
3. Occlusal testing: Confirm uniform occlusal contact with occlusal paper, ensuring no interferences during protrusive or lateral movements.

Clinical application of full-contour HT/UT zirconia fixed partial denture restorations

The pre-restoration design for full anatomical fixed partial denture restorations is essential, involving the transfer of the ideal restoration morphology to an intraoral mock-up for the patient, simulating the final restoration effect and guiding tooth preparation based on the ideal restoration shape.[59] The pre-restoration design for full anatomical fixed partial denture restorations focuses on two main objectives: functional reconstruction and aesthetic reproduction. The workflow of "pre-restoration design → mock-up simulation → guided preparation" for full anatomical fixed partial denture restorations essentially converts abstract restoration goals into operable physical references through a "beginning with the end" logic. It ensures functional and aesthetic effects of the restoration while maximising the protection of tooth structure, representing the core technical path of modern precision restorative dentistry.

Tooth preparation and impression

The absence of veneering porcelain fundamentally alters the space requirements for the restoration. In conventional setups, the preparation must account for both the framework and the overlying porcelain, necessitating more extensive tooth reduction. However, with full-contour zirconia, the restoration space is solely dedicated to ensuring two key objectives: maintaining ideal mechanical properties and achieving superior aesthetic effects. This dual focus allows clinicians to tailor the preparation more precisely, as they no longer need to accommodate the thickness demands of an additional porcelain layer.

Mechanical considerations in this context involve ensuring that the zirconia restoration has sufficient bulk to withstand the occlusal forces exerted in the oral cavity. Meanwhile, aesthetic goals require that the material's inherent translucency and colour characteristics be leveraged effectively, which often depends on factors such as the restoration's thickness and the underlying tooth structure. By aligning the preparation specifically with these two criteria, dental practitioners can optimise the balance between tissue preservation and restoration performance.

Edge preparation for fixed partial denture restoration

With regard to edge position, the choice of marginal placement, whether supragingival, equigingival or subgingival, requires a thorough assessment that considers retention needs, aesthetic goals, the presence and condition of a dentine ferrule, and the specific type of marginal preparation.[60] This decision is crucial for ensuring both the functional durability and aesthetic integration of the restoration, while also protecting periodontal health.

1. Horizontal tooth preparation: In cases of horizontal marginal designs, the clinician has the flexibility to choose between supragingival, equigingival or subgingival margins. This flexibility stems from the adaptability of horizontal preparation to different clinical scenarios. Regardless of the chosen position, the finishing line of the prepared tooth must exhibit uncompromised clarity, smoothness, and continuity. These characteristics are essential for ensuring precise impression taking, accurate restoration fabrication and optimal marginal adaptation, which in turn prevent microleakage and potential secondary caries.
2. Vertical tooth preparation: Vertical marginal configurations typically necessitate subgingival placement to form a distinct band-shaped finishing area. This design is often employed in cases where enhanced retention and resistance form are paramount, such as in full-coverage restorations for teeth with signifi-

cant structural loss. The subgingival positioning in vertical preparation allows for a more extensive and uniform marginal seal, while the band-shaped finish provides a clear boundary for both the preparation and the subsequent restoration. This configuration not only maintains the mechanical integrity of the restoration but also promotes better aesthetic integration, especially in areas with minimal gingival display.[61]

3. Biological width: A fundamental principle in both horizontal and vertical tooth preparations is the uncompromised preservation of the biological width. Careful measurement and planning are crucial during the preparation stage to guarantee that the marginal position, no matter its type, stays at a safe distance from the biological width. This process demands a thorough understanding of anatomical landmarks, accurate clinical technique and often the use of diagnostic tools like periodontal probes and radiographs to guide preparation. Following these principles helps clinicians balance restorative requirements with periodontal health, promoting the long-term success of the dental restoration.

Edge preparation for anterior full crowns is 0.3 to 0.7 mm, whereas for posterior crowns it is 0.5 to 1.0 mm.

Axial and occlusal surface preparation for fixed partial denture restoration

Axial surface preparation for crown restoration is 0.7 to 1.0 mm, and incisal and occlusal surface preparation is 1.0 to 1.5 mm. The key points of tooth preparation for fixed partial denture restoration are consistent with those of crown restoration. Attention should be paid to obtaining a common path of insertion between the abutment teeth.

Impression technology

Impressions can be taken via traditional or digital methods. Digital impressions are preferred for higher precision, improved efficiency and a better patient experience.[62] The impression should clearly capture the overall shape of the prepared tooth, especially the shape of the finish line or finish area.

Digital design of full-contour fixed partial denture restoration

The goal of full-contour zirconia restorations is to achieve harmony in masticatory function, aesthetics and long-term stability by accurately replicating natural tooth morphology and applying scientific thickness design.

Digital morphology design of full-crown and fixed partial denture restoration

Natural teeth have complex anatomical structures, including the shape of the crown, the morphology of the occlusal surface, the proximal contact relationship and surface texture. The characteristics of the crown shape include:

1. Axial surface convexity: The convexity of the buccal and lingual surfaces should be consistent with that of natural teeth to maintain gingival health. Excessive convexity may lead to gingival recession, while insufficient convexity may cause inflammation.
2. Cervical margin morphology: The cervical curve should be coordinated with adjacent teeth to avoid steps or overhangs, ensuring a seamless fit between the restoration margin and the tooth structure.
3. Surface texture: Simulate fine structures of natural teeth such as developmental grooves, ridges and pit grooves through carving or digital design to enhance the realism of the restoration.

The margin of the restoration should coincide with the finish line or finish area of the prepared tooth.

Thickness of fixed partial denture restoration

Although HT/UT zirconia restorations have high strength, insufficient thickness of the restoration may lead to chipping, fracture or undesirable show-through of the underlying colour (such as when the abutment tooth is heavily discoloured). Full-contour restoration requires a reasonable thickness design (Table 2) and cross-sectional area of connector (Fig 6) that balances mechanical properties and tooth preparation volume.[63]

Material selection

Choose a suitable material shade based on the colour and translucency effect, considering the colour and strength distribution of the zirconia. Also, specify the restoration's spatial position within the zirconia block.

Clinical try-in and occlusal adjustment

Pre-simulate occlusal contact points through digital design software to establish occlusal contact and reduce manual occlusal adjustment. After sintering, full-con-

Table 2 Thickness of full-crown and fixed partial denture restoration and cross-sectional area of connector.

Type of restoration		Axial surface	Occlusal surface	Connector
Full crown	Anterior	0.7–1.0 mm	1.0–1.5 mm	NA
	Posterior	0.7–1.0 mm	1.0–1.5 mm	NA
Fixed partial denture	Anterior	1.0–1.5 mm	1.0–1.5 mm	7–12 mm^2
	Posterior	1.0–1.5 mm	1.0–1.5 mm	9–12 mm^2

NA, not applicable.

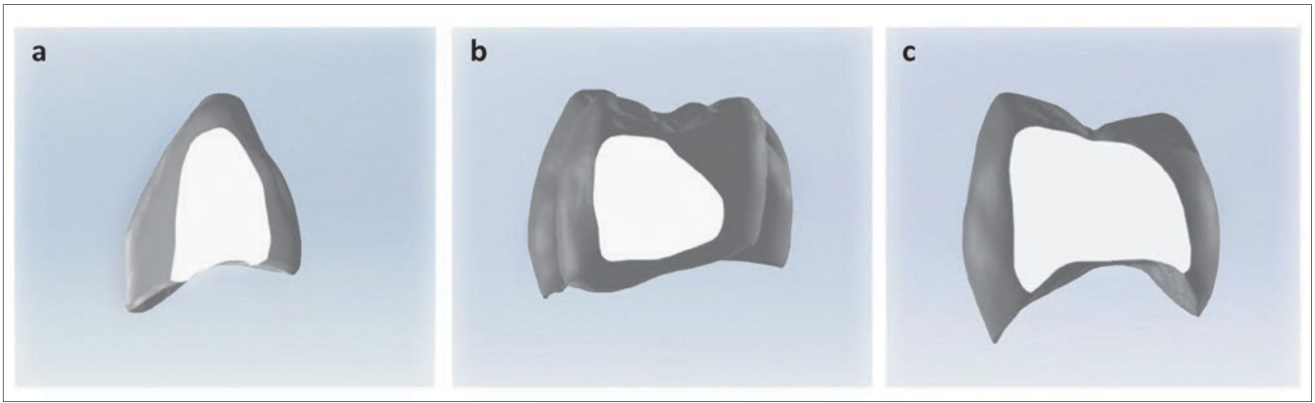

Fig 6a to c Digital design of the cross-sectional area of the connector of the fixed partial denture: 7 to 12 mm^2 for the anterior region **(a)**, at least 9 to 12 mm^2 for the premolar region **(b)** and at least 9 to 12 mm^2 for the molar region **(c)**.

tour restorations are delivered to the clinic for try-in. During this, check the marginal position, proximal contact, and occlusal relationship. Fine-grit diamond burs can be used for minor grinding, while extensive grinding and grinding of the critical structure (e.g., fixed bridge connector area) should be avoided as much as possible. Sequential polishing treatment is required after grinding.

Bonding of full-crown and fixed partial denture restorations

Surface treatment of zirconia

It is advisable to use an alkaline treatment agent to clean the tissue surface and dissolve protein contaminants.

Selection of bonding materials

It is advisable to use a pretreatment agent that contains acidic functional monomers (such as 10-Methacryloyloxydecyl dihydrogen phosphate, 10-MDP monomer) along with a conventional dual-curing resin cement, or to use a dual-curing resin cement that contains acidic functional monomers.[64,65]

Clinical application of full-contour HT/UT zirconia veneer restorations

The advent of full-contour HT/UT zirconia marks a revolutionary change in aesthetic restorative dentistry. It eliminates the difficult choice between the superior aesthetics of glass-ceramics and the enhanced strength of traditional zirconia. Clinicians now have a material that effectively bridges this gap, providing a strong, conservative and aesthetically pleasing solution for a variety of clinical challenges, especially in the anterior region.[66,67]

By understanding the science behind the material, adhering to conservative preparation principles, leveraging the precision of the digital workflow and mastering the critical bonding protocols, clinicians can confidently incorporate HT and UT zirconia veneers into their practice. These restorations aim to fulfil the high aesthetic expectations of today's patients while also ensuring the strength and durability needed for long-term clinical success.

Indications for full-contour HT/UT zirconia veneer

The unique combination of strength and beauty in HT and UT zirconia offers a wide range of clinical options for veneers. The choice to use these materials depends on several factors, many of which are outlined in the provided clinical document.

High requirements for restoration strength

While lithium disilicate offers excellent aesthetics, its flexural strength (typically 360 to 500 MPa)[68,69] can be a limitation in certain situations. HT zirconia boasts a flexural strength of 720 MPa or higher, while UT zirconia, though less strong, still surpasses lithium disilicate at around 550 to 600 MPa.[12,70] This makes zirconia veneers an excellent choice for patients with a history of restoration fracture, those with parafunctional habits like bruxism (with careful occlusal management) or in cases where the veneer needs to withstand significant functional forces.[71]

Minimally invasive restorations

The thickness of veneer restoration is within the range of 0.3 to 1.0 mm, and the tooth preparation should be controlled within the enamel layer as much as possible. As noted, the thickness of an ultra-thin zirconia veneer can be as minimal as 0.3 to 0.5 mm.[12] This facilitates a highly conservative approach to tooth preparation, often allowing the clinician to remain entirely within the enamel. This "micro-preparation" or even "no-prep" approach is ideal for preserving tooth structure, which is the cornerstone of modern restorative dentistry. It is particularly advantageous for treating peg laterals, closing diastemas or making minor cosmetic enhancements without aggressive tooth reduction.[10]

Multi-tooth aesthetic restorations

When restoring multiple anterior teeth, achieving a uniform and predictable aesthetic outcome is paramount. Zirconia's stability and the precision of the CAD/CAM process ensure consistent shade matching and morphology across multiple units.[11,72] Multi-layered zirconia blocks mimic the natural colour and translucency gradient from cervical to incisal edge, enabling lifelike smile makeovers. Highly translucent materials like feldspathic porcelain or lithium disilicate struggle to mask severely discoloured teeth. Although HT and UT zirconia improve their translucency, they remain more opaque than glass ceramics.[10,12]

Tooth preparation for full-contour HT/UT zirconia veneers

A successful veneer restoration begins with a meticulous and conservative tooth preparation. The goal is to create sufficient space for the restorative material without weakening the tooth, while ensuring a clear path for insertion and a definitive margin.[73]

Margin design

Edge preparations are the same as those for fixed partial denture restorations. For horizontal margins, the preparation should terminate in a clear, continuous chamfer or a modified shoulder margin, typically 0.3 to 0.5 mm in depth.[12] For vertical margins, the band-shaped finish provides a clear boundary for both the preparation and the subsequent restoration.[73,74]

Axial surface preparation of zirconia veneers

Zirconia veneer preparation should be limited to the enamel layer to ensure a strong and predictable bond.

With ultra-thin veneers (0.3 to 0.5 mm), for minimal colour adjustment or additive morphology corrections, a facial reduction of 0.3 to 0.5 mm is sufficient.[73,75] This is achieved using depth-cutting burs to ensure uniform tooth surface reduction.

With conventional veneers (0.5 to 1.0 mm), for cases requiring more significant changes in contour or shade or to mask underlying discolouration, a greater reduction of 0.5 to 1.0 mm is necessary.[67,73]

Digital design and fabrication of zirconia veneer restoration

The fabrication of zirconia veneers is a fully digital process, leveraging CAD/CAM technology to deliver restorations with unparalleled precision and consistency.

Digital design of veneer restoration

Before designing the morphology of veneer restoration, it is essential to consider personalised characteristics, adjacent relationships and occlusal relationships. For the anterior tooth area, the impact of shape on pronunciation is also considered. The process begins with a digital impression taken with an intraoral scanner or by scanning a conventional physical model. This 3D model is then imported into the CAD software. The dental technician, in collaboration with the clinician, designs the virtual veneer.

1. Aesthetics: The morphology, surface texture and incisal edge position are designed to harmonise with the patient's facial features and adjacent teeth.
2. Function: The occlusal and phonetic relationships are carefully evaluated to ensure the restoration will function correctly.

3. Material selection: The designer needs to choose a suitable zirconia block to match the target shade and translucency, then position the veneer within the block to achieve the desired colour gradient.[10,67]
4. Thickness: The software ensures the design adheres to the minimum thickness requirements (0.3 to 0.5 mm for ultra-thin and 0.5 to 1.0 mm for conventional) for structural integrity.[73,75]
5. Margin design: The edge design of veneer restorations is similar to that of full-crown and fixed partial denture restorations.

Fabrication of zirconia veneer restoration

After finalising the design, the file is transferred to a milling machine, which precisely carves the restoration from a pre-sintered zirconia block. After milling, the "green state" or "white state" restoration is delicate and oversized to account for shrinkage. It is then placed in a sintering furnace, where it is heated to high temperatures (around 1450°C to 1550°C). During sintering, the zirconia particles fuse together and the restoration shrinks to its final, dense and strong state.[76,77]

After sintering, the tissue surface of the veneer is treated for bonding. The procedure for zirconia surface silicatisation[78-81] involves cleaning the tissue surface of zirconia veneers with steam, fixing the veneer restorations, spraying a thin layer of lithium silicate on the tissue surface and sintering it into a silicate layer. After silicatisation, the labial surface can then be characterised with stains to add subtle details, mimic incisal translucency and create a layered texture that rivals natural enamel under various lighting conditions.[12,72]

Bonding of veneer restorations

A durable bond between the veneer and the tooth is arguably the most critical factor for long-term clinical success of zirconia restorations.[82] Unlike glass-ceramics, which can be etched with hydrofluoric acid to create micromechanical retention, zirconia's polycrystalline, acid-resistant nature requires a different approach focused on a combination of mechanical and chemical adhesion.[83,84]

Surface treatment of the veneer restoration

1. Airborne-particle abrasion: The most important step for creating micromechanical retention is to sandblast the tissue surface of the veneer with 50-µm aluminium oxide particles at low pressure (approximately 1.5 Bar or 20 to 25 psi) from a distance of 10 mm.[83] This gently roughens the surface, increasing the surface area for bonding without causing significant damage that could compromise the material's strength.[82,84]
2. Cleaning: After try-in, salivary phosphates can contaminate the veneer surface, hindering bonding due to their high affinity for zirconia. Therefore, it is crucial to thoroughly clean the surface, which can be effectively achieved using a dedicated cleaning agent with an alkaline solution.[85,86]
3. Priming (chemical adhesion): After cleaning and drying, a special ceramic primer needs to be applied. For zirconia, it is imperative to use a primer containing the acidic functional monomer 10-MDP. MDP has the unique ability to form a strong, durable chemical bond directly with zirconium oxide, creating a powerful link between the resin cement and the veneer.[82,86,87]
4. Silica coating (silicatisation): An alternative or additional step involves coating the zirconia surface with a thin layer of silica-based ceramic. This can be done in the laboratory by applying and firing a thin layer of lithium silicate. This forms a glass-ceramic surface on the zirconia, which can then be etched with hydrofluoric acid and treated with a conventional silane coupling agent, similar to glass-ceramics.[88-90]

Selection of bonding materials

The choice of luting cement is crucial. Dual- or light-curing resin cement is recommended. For optimal results, clinicians should select a resin cement that contains the 10-MDP monomer, thereby creating a continuous chemical bond between the tooth and the veneer.[83,88,91] Cement shade selection influences the final aesthetics, especially with thin, translucent veneers. Therefore, it is recommended to use try-in pastes to choose the right cement shade prior to final bonding.

Clinical application of full-contour HT/UT zirconia implant-supported restorations

HT/UT zirconia ceramics have achieved a paradigm shift in the field of implant-supported restorations, especially in areas where both aesthetic and functional results matter most. Their adoption depends on three key advantages: high flexural strength, excellent biocompatibility shown by minimal inflammatory responses and optical properties that closely resemble natural dental tissues. Clinically, the success of these restorations depends on evidence-based digital design and standardised fabrication protocols. These protocols need to consider different retention methods, specifically screw-retained versus cement-retained configurations, and address complex clinical situations, such as full-arch edentulous rehabilitations.

This section aims to systematically analyse the technical complexities, material science factors and step-by-step clinical workflows essential to the digital design and additive manufacturing of full-contour zirconia implant prostheses.

Digital design and fabrication of implant-supported fixed partial denture restorations

Digital design of screw-retained one-piece restorations

Innovations in implant and ceramic technology now enable screw-retained prostheses to achieve aesthetic, functional and biological results comparable to those of cement-retained prostheses, while offering the benefits of predictable retrievability and eliminating residual cement.[92] Zirconia's natural aesthetic qualities allow it to closely resemble natural teeth, making it an ideal choice for dental implant restorations.[93,94]

Screw-retained one-piece restorations include single crowns, multiple contiguous crowns, anterior tooth single-ended partial dentures (with one unit cantilever) and anterior three- or four-unit fixed partial dentures (including one or two pontic units).

The digital design process for such restorations demands meticulous attention to structural integrity, aesthetic integration and functional stability.

1. Minimum thickness around screw channels: The restoration must maintain a minimum thickness of 0.8 mm around the screw channel.[95] This dimension is non-negotiable as it prevents fracture under occlusal loading. Digital design software (e.g., Exocad [Darmstadt, Germany], 3Shape [Copenhagen, Denmark]) includes tools to visualise and enforce this thickness, with real-time alerts if the design falls below the threshold. Thinner sections risk fatigue failure over time, particularly in UT zirconia, which may have slightly lower flexural strength compared to traditional 3Y-TZP.
2. Aesthetic zone considerations: In anterior regions, the labial surface of the restoration demands special attention. When paired with a metal abutment, the labial thickness of the zirconia restoration must reach a minimum of 1.5 mm to effectively mask the underlying metal and prevent greyish discoloration of the gingival margin, a common aesthetic compromise with thinner restorations.[96] UT zirconia, with its higher light transmittance, relies on this thickness to balance translucency and opacity, ensuring the restoration blends seamlessly with adjacent natural teeth. Digital shade mapping tools can simulate the labial thickness and predict light interaction, guiding adjustments before fabrication.
3. Gingivo-occlusal distance (GO distance): For screw-retained restorations, the GO distance (vertical space from the gingival margin to the occlusal surface) must be at least 5 mm.[94,97-99] This dimension ensures sufficient space for screw placement, adequate material bulk for strength and secure retention. A GO distance of less than 5 mm increases the risk of screw loosening, restoration fracture or failure to achieve proper occlusal anatomy. In cases with limited vertical space (e.g., posterior regions with bone resorption), clinicians may opt for shorter screws or platform-switching implants to maximise the available GO distance, but the 5-mm threshold remains a benchmark for predictable outcomes.
4. Screw-retained three- or four-unit fixed bridge restoration: This can be used for screw-retained three- or four-unit fixed partial denture restoration supported by implants in the anterior region, and necessitates that the implants have proper 3D placement, with screw access points on the lingual side and good parallelism between them.[100,101] For multi-unit restorations, the connector design of HT/UT zirconia should be sufficiently robust to withstand masticatory forces.[102]

Surface treatment of screw-retained restorations

The surface treatment of screw-retained restorations is bifurcated based on their intraoral position (supragingival vs subgingival) to optimise aesthetics and peri-implant health.

1. Supragingival portion: Custom staining and glazing are employed to mimic the natural tooth's chromatic nuances, such as incisal translucency, cervical shading or subtle enamel striations. HT zirconia's ability to transmit light allows these stains to integrate naturally with the underlying material, avoiding the "blocky" appearance common with less translucent ceramics. Glazing not only enhances aesthetics but also creates a smooth, impermeable surface that resists plaque accumulation.
2. Subgingival portion: Polishing is prioritised over glazing in subgingival areas to achieve a mirror-like surface finish (Ra < 0.2 μm). A smooth surface minimises bacterial adhesion and facilitates gingival epi-

thelial attachment, reducing the risk of peri-implantitis.[46,57,58] Polishing protocols typically involve sequential use of diamond-impregnated rubber cups and silica-based pastes, ensuring no residual abrasive particles remain to irritate soft tissues.

Digital design and fabrication of cement-retained restorations

Cement-retained restorations, which include a custom outer crown and either a prefabricated or custom abutment, are preferred in aesthetic areas where screw access holes could detract from the appearance. They offer greater flexibility in achieving ideal emergence profiles and contouring, critical for natural-looking gingival architecture. However, their success depends on precise design of the outer crown and abutment to ensure sufficient material thickness and cement space.

Outer crown of cement-retained restorations

1. Minimum thickness requirements: The axial walls of the outer crown must be at least 1.0 mm thick to withstand lateral occlusal forces, while the occlusal surface requires a minimum thickness of 1.5 mm to resist wear and fracture. These dimensions are particularly important for UT zirconia, which, despite advancements, remains more susceptible to chipping under heavy occlusal loads compared to traditional zirconia.
2. Gingivo-occlusal distance (GO distance): To ensure the strength and durability of HT/UT zirconia restorations and prevent chipping or fracture caused by occlusal forces, when the cement-retained method is adopted, the posterior region requires at least 6 mm vertical restoration space.[103]
3. Emergence profile and contour: The outer crown's emergence profile, from the gingival margin to the occlusal third, is designed to replicate the natural tooth's gradual taper, promoting healthy soft tissue architecture. Over-contoured axial walls can compress gingival tissues, leading to inflammation, while under-contoured designs may result in food impaction and soft tissue recession.

Abutment selection and customization

Abutment design is crucial for cement-retained restorations, affecting crown fit and thickness. It involves two main steps:

1. Finalise outer crown shape: The outer crown's entire outline is initially designed, taking into account both aesthetic and functional needs. This process involves establishing the optimal occlusal anatomy, proximal contacts and labial/buccal contours.
2. Abutment selection/design: For straightforward cases with adequate bone and soft tissue volume, standard prefabricated abutments are selected. The abutment's height and diameter are chosen to ensure the outer crown can achieve the required 1.0 mm axial and 1.5 mm occlusal thickness. In complex cases, such as those with angled implants, limited interocclusal space or irregular soft tissue contours, custom abutments are designed. These abutments are milled from titanium or zirconia to compensate for implant angulation, optimise soft tissue support and create a uniform cement space (typically 30 to 50 µm). Customised zirconia abutments provide better aesthetic integration with HT outer crowns by eliminating the greyish tint of metal abutments.

Digital design and fabrication of the superstructure of fixed restorations supported by implants in the edentulous arch

Monolithic zirconia crowns demonstrate superior mechanical reliability, fewer technical complications and comparable biological outcomes. It can be used for the outer crown portion of fixed restoration or over the implant-supported framework in edentulous arches (complete anodontia).[104-108] It is important to remember that the wide clinical use of translucent zirconia for full-arch implant prostheses is limited by its reduced flexural strength and fracture toughness compared to high-strength opaque zirconia. A novel proof of concept for FP1 full-arch prosthesis featured by translucent monolithic zirconia and titanium framework was presented.[108] Further long-term studies are recommended to validate monolithic zirconia crowns over the implant-supported framework in edentulous arches.

Framework design

The framework forms the structural foundation of the superstructure, transferring occlusal forces to the implants. Two primary materials are used:

1. Titanium frameworks: Known for their high strength-to-weight ratio and flexibility, titanium frameworks are ideal for long-span bridges in edentulous arches. They have excellent fatigue resistance and are suitable for patients with high occlusal forces, like bruxers. However, their greyish colour needs careful masking with zirconia.

2. 3Y-TZP zirconia frameworks: These offer superior aesthetics compared to titanium, as their white colour eliminates the need for extensive shading. They are recommended for cases where aesthetic demands are paramount and sufficient gingival-occlusal height (14 to 16 mm) is available. 3Y-TZP's high fracture toughness (~6 to 8 $MPa \cdot m^{1/2}$) ensures durability, though it is more rigid than titanium, requiring a precise passive fit to avoid implant overload.
3. A critical design feature for both materials is the back-cut, a tapering of the framework's axial walls to create space for the outer crown. This back-cut (typically 2 to 3 degrees per wall) ensures the outer crown can achieve uniform thickness while allowing for natural light transmission.

Outer crown design over the framework

The outer crown, fabricated from HT/UT zirconia, is designed to encapsulate the framework while meeting aesthetic and functional criteria:

1. Thickness requirements: Over 3Y-TZP frameworks, in aesthetic zones, the outer crown's axial and occlusal thickness measures 1.0 to 1.5 mm.[95] This range strikes a balance between translucency and durability, enabling light transmission while maintaining structural strength. Over titanium frameworks, a minimum thickness of 1.5 mm is required in aesthetic zones to mask the framework's grey colour. UT zirconia's higher light transmittance necessitates this increased thickness to prevent grey show-through at the gingival margin.
2. Shading and colour matching: Digital shade mapping tools analyse the adjacent dentition and soft tissues to generate a personalised colour map for the outer crown. Stains are then applied to mimic natural tooth features, ensuring the restoration seamlessly integrates with the patient's smile.

Use of shading adhesives

When pairing titanium frameworks with HT/UT zirconia outer crowns, shading adhesives are indispensable.[109] These adhesives, available in a range of shades (A1 to D4), are applied between the framework and outer crown to mask titanium's grey hue. They also strengthen the bond between the two components, lowering the risk of delamination. The adhesive is cured either by light activation or chemically, resulting in a strong, colour-stable bond interface. Clinicians must ensure complete coverage of the framework with the adhesive, particularly in thin areas (e.g., cervical margins), to avoid aesthetic discrepancies.

Occlusal adjustment of fixed restorations supported by implants in the edentulous arch

When the opposing teeth are natural teeth or fixed restorations on natural teeth

Natural teeth have proprioception, which makes them very sensitive to contact points during biting. The main goals of occlusal adjustment are to:

- ensure uniform distribution of occlusal contacts across the dental arch;
- eliminate premature contacts and occlusal interferences that could lead to excessive force on specific teeth;
- ensure smooth and unobstructed occlusal trajectories during lateral and protrusive movements, allowing the mandible to move without abrupt shifts or jolts.

These adjustments prevent localised overloading of natural teeth, reduce the risk of enamel wear or microfracture and preserve the stability of the stomatognathic system.

When the opposing teeth are implant-supported fixed restorations

Implants lack proprioception, meaning they cannot perceive or adapt to excessive occlusal forces. Occlusal adjustment priorities include:

- achieving uniformly distributed occlusal contacts to avoid concentrated stress on individual implants, which could lead to implant loosening or bone resorption;
- establishing a group function occlusion, where multiple teeth share occlusal forces during lateral movements, distributing the load across the implant-supported prosthesis;
- creating a shallow incisal guidance angle in the anterior region, with anterior guidance activated during protrusive movements to protect posterior implants from excessive force;
- eliminating occlusal interferences in the posterior region during lateral excursions, ensuring smooth movement without abrupt contact;
- establishing light contacts on cantilever segments or pontics to minimise leverage forces that could compromise the prosthesis or implant stability.

When the opposing teeth are implant-supported overdentures

For implant-supported overdentures, occlusal adjustment focuses on:

- ensuring uniform occlusal contacts across the denture base to prevent uneven loading on implants and supporting soft tissues;
- establishing a balanced occlusion where contacts are evenly distributed between the maxillary and mandibular dentures during centric, lateral and protrusive positions, reducing denture displacement;
- creating a centric freedom zone (a small range of mandibular movement within centric relation without occlusal interference), allowing comfortable arch positioning and minimising strain on implants and surrounding tissues.

Conclusion

HT/UT full-contour zirconia restorations are increasingly adopted in clinical practice thanks to their superior aesthetic effects and reliable mechanical performance. To promote standardised use in clinical practice, improve restoration quality and ensure patient safety and treatment efficacy, relevant professional organisations have established specific standards that address material properties, clinical indications, digital design and manufacturing requirements, quality control and evaluation. This offers systematic and scientific guidance for dental professionals. The implementation of these group standards is expected to harmonise clinical practice, advance the quality of HT/UT zirconia restorations and provide patients with restorative solutions that are superior, safer and more predictable.

Conflicts of interest

The authors declare no conflicts of interest related to this study.

Author contribution

Drs Shi Ming LIU, Ya Ke WANG, and Chen Min YAO drafted the original manuscript; Drs Jie Fei SHEN, Wei Cai LIU, Li Na NIU, Chun XU, Chu Fan MA, Zhe WU, Ke ZHAO, Dan Dan PEI, Hong Bo LI, Ya Ming CHEN, Yu Wei WU, Jun Ling WU, Xiao Dan SUN, Hai Lin LIU, Fei Lie ZHONG, Zhuo Qun YAN, Hai Yan WU, Mou Shan LIU, Hong Chang LAI, Jun Yu SHI, Zhong Hao LIU and Yi MAN contributed to the review and editing of the manuscript; Drs Feng LIU and Cui HUANG contributed to the conceptualisation and investigation and supervised the project. All authors read and approved the final version.

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