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From Conventional Zirconia to Hyper-Translucent Zirconia: An Over View

Siham Kouji[1*], Hicham Soualhi[2], Amal El Yamani[3]

[1]Resident, Department of Fixed Prosthodontics, Mohamed V University, Faculty of Dental Medicine of Rabat, Morocco
[2]Professor of Superior education, Department of Fixed Prosthodontics, Mohamed V University, Faculty of Dental Medicine of Rabat, Morocco
[3]Professor of Superior Education, Head of the Department of fixed Prosthodontics, Mohamed V University, Faculty of Dental Medicine of Rabat, Morocco

Abstract	Review Article

Zirconia is one of the materials with several advantages including excellent mechanical and biological behaviors that provide numerous indications in various clinical situations. Because the opaque appearance of zirconia negatively affects the aesthetic outcome, layering materials have been proposed to mask this appearance. However, porcelain chipping is considered one of the most common technical problems in veneered zirconia crown. To overcome the problem of poor optical properties, translucent monolithic zirconia was introduced to fabricate multi-unit monolithic crown without increased risk of porcelain fracture or reduced esthetic properties of the core material. However, this material must be further studied in vitro and in vivo to determine its long-term ability to maintain its exceptional properties. The aim of this article is to provide an overview of the dental zirconia (Zir) revolution, including its types, properties, applications and cementation procedures.

Keyword: dental prostheses, ceramics, translucency, cementation, full ceramic, monolithic zirconia restorations, hyper-translucent zirconia, veneered zirconia restorations, zirconia.

INTRODUCTION

With growing interest in aesthetics and concerns about toxic and allergic reactions to certain alloys toxic and allergic reactions to certain metal alloys, patients and dentists are looking to metal-free dental restorations. So, the development of Highly durable dental ceramics came to dominate the late 20th century [1, 2].

Zirconia has been known since ancient times. Its name comes from the Arabic word "Zargun" (Golden colour) [3]. Zirconia is a crystalline zirconium dioxide ($ZrO2$). Zirconium was first used for medical purposes in 1969 for orthopaedic applications. It was proposed as a new material, for the replacement of hip heads, instead of titanium or alumina prostheses [4].

Zirconia is a polycrystalline ceramic. Unlike glass, which is an amorphous structure, its shape is repeated in all three planes of space.

Like all dental ceramics, the various types of zirconia available on the market are inorganic materials made up of oxides whose atoms are linked together by strong iono-covalent bonds, making them highly rigid and melting at high temperatures.

The oxides used to fabricate zirconia prostheses, principally zirconium oxide ($ZrO2$ or zirconia), are produced in the form of powders sintered at high temperature (around 1,500°C). Sintering is a thermal treatment that transforms an agglomerate of grains into a dense solid.

In practice, the prosthesis is milled in a CAD/CAM block made of pressed powder, which resembles chalk, then sintered in a specific furnace following a precise protocol, which varies from one material to another.

Since sintering causes the material to contract by around 30%, the prosthesis is machined to an oversized shape to compensate for this sintering

contraction. In contrast to this 'soft milling' process, there are 'hard milling' processes, in which the prosthesis is milled from a block of zirconia that has already been sintered. However, these processes are tending to disappear due to the high cost of milling and the risk of material deterioration.

Zirconia is one of the materials with several advantages including excellent mechanical and biological behaviors that provide numerous indications in various clinical situations [5, 6]. Because the opaque appearance of zirconia negatively affects the aesthetic outcome [7], layering materials have been proposed to mask this appearance. However, porcelain chipping is considered one of the most common technical problems in veneered zirconia crown [8].

To overcome the problem of poor optical properties, translucent monolithic zirconia was introduced in 2011 to fabricate multi-unit monolithic crown without increased risk of porcelain fracture or reduced esthetic properties of the core material. In situation where the restoration should withstand higher stress, this material is claimed to combine good esthetic property with load bearing capacity [9]. The present article aims to review the evolution of zirconia and put the point on different characteristics of monolithic translucent zirconia.
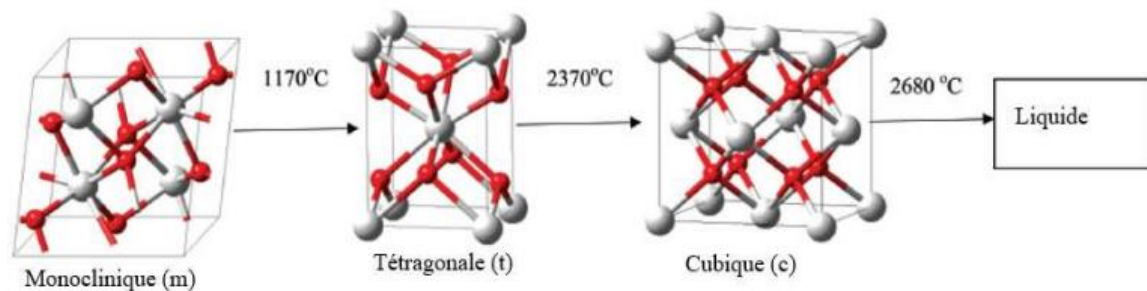

Figure 1: Crystallographic phase change with temperature variation of the three phases of ZrO2 [68]

Evolution of zirconia

Zirconia materials are under the category of polycrystalline ceramics, which are composed entirely of crystals like alumina. In contrast, glass-ceramics and infiltrating ceramics, which are the other two families of dental ceramics, have a glassy phase composed of silica oxide. The other two families of ceramics can also be made using conventional methods, but polycrystalline ceramics can only be produced using Computer Aided Design and Manufacturing (CAD-CAM) techniques.

Pure zirconia has 3 principal phases: Monoclinic at room temperature and remains stable up to ~1170°C. Above this temperature, it transforms into the Tetragonal(t) phase, which exists up to the melting point of ~ 2370°C, and then into the Cubic phase. During cooling, the Tetragonal phase is reconverted to Monoclinic at a temperature below ~1070°C [10]. The last transformation, from the tetragonal to the monoclinic phase, is also described as the martensitic transformation and is characterized by a volume increase of about 4% causing significant stress generation in the material leading to fracture.

This abrupt increase in volume during the cooling phase makes it impossible to produce sintered ceramics from pure zirconia, this is why manufacturers have sought´ to stabilise the structure of ZrO2-based ceramics either in the tetragonal phase or in the cubic phase. by the addition of stabilizing oxides, which are incorporated into the crystal lattice of the zirconia. The zirconia most commonly found on the market is stabilized with yttrium oxide (Y-TZP).

Traditional or first-generation zirconia is a ceramic partially stabilized by 3% yttrium oxide (3Y-TZP) in the tetragonal phase [11]. At the sintering temperature of zirconia (1500°C), both tetragonal and cubic phases coexist. If we maintain the tetragonal phase at low temperature, we obtain a material composed mainly of tetragonal phase, but also containing cubic phase at a rate of around 15% for 3Y-TZP. The resulting zirconia is then metastable: any energy input (e.g. shock or mechanical stress) can cause it to evolve towards the stable state (monoclinic phase).

This allotropic character gives it the ability to fight microcrack propagation by changing from tetragonal to monoclinic form (with a 4% increase in volume) when subjected to stress (mechanical or thermal) [12, 13]. By increasing crystal volume, this transformation potential enables the crack to be compressed, thus preventing its propagation. This property gives zirconia high toughness (resistance to crack propagation), and a flexural strength far superior to that of glass-ceramics, from 900 to 1250 MPa [14], thanks to the unique presence of crystals in its composition.

It is therefore well-suited to the creation of monolithic crowns in the posterior region, for example, when the support is colored or when mechanical strength

is paramount. It is also often used as a substructure material, as its polycrystalline nature gives it high mechanical strength, while its high reflectivity masks underlying colored or metallic substrates. On the other hand, it is contraindicated in the anterior sector due to its opaque appearance, which results from its high reflectivity. The refractive index (at visible wavelengths) of zirconia is approximately 2.21 (that of lithium disilicate is 1.55, and that of alumina 1.76) [15].

The opaque appearance of zirconia is thought to be due to the interaction between the typical grain size of dental zirconia (about 0.4 µm) versus the wavelength of light (about 0.1 to 0.7 µm), mismatch between the particle particles and the matrix, and the presence of monoclinic, cubic, and tetragonal phases that also have different refractive indexes [16, 17]. These factors cause alternative light scattering. Because it transmits through the material and is responsible for its opaque appearance [18].

Therefore, the major problem with veneered zirconia (3Y-TZP) is the risk of chipping or fracture of the veneering ceramic under the effect of occlusal forces. As a result, the survival rate of a prosthesis with a zirconia infrastructure is lower than that of a prosthesis with a metal infrastructure because of the greater risk of chipping [19, 20]. Consequently, chipping remains the limiting factor in the use of these crowns, which has encouraged the development of new zirconiums that can be used in the monolithic technique.

To address the optical deficiency of more opaque zirconia and to overcome the problem of chipping many efforts have been made with the basic strategy of varying the crystal size and bringing the refractive index of the crystalline phase and the matrix phase closer together [18].

With the aim of improving monolithic ceramics with acetable translucency, A 2nd generation of zirconia then appeared: it is still a zirconia stabilised by 3% yttrium (3Y-TZP) but its optical properties have been improved for greater translucency. However, aesthetics are acceptable for posterior restorations, but remain far inferior to other types of ceramics. In addition, ageing is increased by the phenomenon 26 of Low Temperature Degradation because monolithic restorations are not protected from contact with water by deglazing ceramics (Fig 4 & 5) [21].

The proportion of yttrium oxide has been increased in the new-generation zirconia 4Y-TZP, 5Y-TZP. This leads to the formation not only of the metastable tetragonal phase but also of the cubic portions of the structure simultaneously. This mixed structure is known as fully stabilized zirconia and represents the third generation, in which, in contrast to the partially stabilized zirconia of the first and second generations, no

transformation of the structuring phases takes place under induced stresses.

Indications

The decision for a material depends on both material-related (esthetic potential, mechanical properties, abrasion behavior of the material and the antagonist) and clinical factors (degree of destruction of the tooth, cementation options, functional aspects). The clinical long-term success is closely linked to the correct indication, the experience and knowledge of the restorative team, as well as suitable cementation and an adequate occlusal concept.

For the fabrication of all-ceramic single crowns in the anterior region, veneered lithium disilicate ceramics or veneered zirconium oxide ceramics (3Y-TZP) should be used. As restorations made of these veneered materials, according to recent data, have very good survival rates of 88.5–100 % after 5 years for zirconium oxide ceramics [13, 21, 33, 45, 48, 50]. Chipping as a technical complication of veneered zirconium crowns has been reported with a frequency of 1.9–8.1 % after 5 years [21, 48]. No statement can be made at present on newer zirconium oxide ceramics (4Y-TZP, 5Y-TZP) due to a lack of clinical data.

For posterior single crowns, monolitic and veneered zirconium are highly recommended, New long-term data are available for veneered zirconium oxide ceramics with good 5-year survival rates of 94–98.1% [21, 33, 46, 48, 62] with moderate chipping rates of 1.9–10 % after 5 years [21, 46, 48, 62]. Expert consensus was expressed for monolithic zirconium oxide ceramics based on short-term data with 100 % survival after 3 years [4]. Due to insufficient scientific long-term data for newer zirconium oxide ceramics (4Y-TZP, 5Y-TZP), no statement for a recommendation of their use in the posterior region can be made (Fig 2 & 3).

For All-ceramic multi-unit/span fixed dental prostheses the clinical data is not sufficient to recommend multi-unit/span all-ceramic FDPs. The few existing studies on veneered zirconium oxide ceramics (3Y-TZP) report that there are increased chipping rates [63] at 35 % after 10 years and increased failures with long-span FDPs. Survival rates are 75% after 10 years for FDPs with up to 4-units [63] and 88.8 % after 7 years for FDPs with up to 6-units.

Figure 2: First-generation 3Y zirconia infrastructure before enameling

Figure 3: Layering cosmetic ceramics on a zirconia infrastructure

Figure 4: First-generation 3y monolithic zirconia single crowns 3y

Figure 5: First-generation monolitic zirconia bridge

Zirconia properties
- *Mechanical properties*

Mechanical properties of zirconia were proved to be higher than those of all other ceramics for dental use. These mechanical capacities cover several aspects, the most important of which are: Compressive strength [during axial movements], Flexural strength [during translational movements] and Toughness [resistance to crack propagation].

Flexion stresses are exerted mainly on the incisivocanine group. The value of *Flexural strength* is ranging between 900 and 1500 MPa. Translucent Zirconia is claimed to be two thirds greater than lithium disilicate [22, 23]. Compressive stress is exerted only during mastication on the occlusal surfaces of molars and premolars. It is 2000 MPa for zirconia and 384 MPa for dental enamel *Toughness* (4 à 5 MPa) is the ability of a material to resist the propagation of a crack. This measurement is used to assess the long-term resistance of a material. Zirconia Y-TZP has a very interesting property: it can undergo a second phase transformation. As a crack progresses, the stabilised tetragonal crystals undergo a monoclinic phase transformation and acquire a 4 to 5% larger volume. The stress field generated by this expansion will then slow down the crack. This phenomenon results in an increase in the material's toughness (Table 1).

Table 1: Flexural strength, fracture toughness, translucency parameter and contrast ratio of different zirconia generations

Zirconia type	Flexural strength (MPa)	Fracture toughness (m1/2)	Translucency parameter**	Contrast ratio
3Y-TZP Opaque	900–1400	4.3–11.5	12–14	0.85–0.88*
3Y-TZPTranslucent	985–1008	4.3–7.0	12–18	0.84–0.89*
4Y-TZP	507–965	3.7–4.4	12.3–12.5	0.79**–0.87***
5Y-TZP	377–644	2.4–4.8	9.1–12.4	0.61–0.75***

- *Propriétés biologiques*

Biocompatibility is the ability of a biomaterial to perform a specific function with an appropriate response from the host. It is assessed by a series of tests given in the ISO standard. Zirconia-based ceramics are chemically inert materials, with no harmful effects or reactions on tissues. The surfaces of ceramic prostheses are polished, which prevents the accumulation of dental plaque. This allows them to come into contact with gingival tissue and help maintain gingival architecture [24, 25].

- Color, translucency and esthetics

Zirconia is generally considered an opaque restorative material with less attractive optical and aesthetic properties than glass ceramics, especially in terms of translucency.

It has been shown that tetragonal zirconia only allows about 25% of incident light to pass through; This characteristic can be advantageously used to cover dark substrates (e.g., metal posts/abutments, dark teeth, etc.) [26].

The color and appearance of monolithic zirconia dental restorations are affected by intrinsic character (grain size and content, yttria content, and amount of impurities) and extrinsic parameters like cement layer, restoration thickness and LTD phenomenon. A study showed a linear correlation between translucency and thickness of ceramic material [27].

Recently, to improve the aesthetic properties of the material, translucent zirconia has been introduced into the market, characterized by the presence of 30-35% cubic crystals. The inclusion of cubic crystals, which are larger than tetragonal crystals, improves the passage of light, with fewer obstacles and porosities. This leads to a reduction in refraction and therefore an improvement in translucency, with more uniform emission of incident light in all spatial directions (Fig 6 & 7).

However, the toughness of translucent zirconia is reduced, compared to tetragonal one, with values of flexural strength ranging between 500 and 900 MPa; as a consequence, translucent zirconia represents a suitable esthetic and mechanical compromise to be preferred in anterior areas up to the first premolars in its monolithic configuration [26, 28].

Figure 6: Posterior crown in translucent zirconia

Figure 7: Monolithic anterior crowns in translucent zirconia

- Low temperature degradation (LTD) and aging

Y-TZP ceramics suffer from a low-temperature degradation phenomenon, a slow transformation from tetragonal to monoclinic phase (T-M transition) that occurs when Y-TZP is in contact with water, steam, body fluids or during steam sterilisation [29], resulting in surface damage. The T-M transition, occurs with micro and macro cracking of the material. These reversions cause local mismatch strains, further driving the microcracks and transferring internal stresses deeper into the subsurface grain by grain. Ultimately, the microcracks coalesce and lead to grain detachment, with consequent degradation in strength [25]. it starts at the surface and progresses into the bulk of the material [30]. Most manufacturers of 3Y-TZ, do not recommend milling or sandblasting to avoid both t $\rightarrow$ m transformation and the formation of surface defects which could be detrimental to long-term performance. The t-m transformation can be reduced by acting on several factors, for example by reducing the grain size, or by increasing the concentration of oxides that stabilise the zirconia [31]. It should be noted, however, that cubic zirconia is less sensitive to t-m transformation than tetragonal zirconia.

Many in vitro studies have interesting on the effect of aging on different zirconia properties: Color, flexural strength, mechanic properties.

Chang-Yuan Zhang *et al.*, summarize the literature related to the effects of aging on the color and translucency of monolithic translucent Y-TZP ceramics, the systematic review concluded that the duration of aging contributed to changes in the translucency and color of the Y-TZP ceramics [32]. Another systematic review reports the same results and confirms that the optical properties for all zirconia materials investigated seem more compromised with increasing aging time, And An increase in monoclinic phase was reported for tetragonal zirconia, while cubic zirconia demonstrates resistance to LTD [33].

Although LTD was found to have no significant effects on the surface roughness of Y-TZP ceramics, the effects of LTD depended on the duration of the steam autoclave process and the specimen preparation [34].

Surface condition and wear of antagonist teeth
Wear on antagonistic teeth is an important and controversial issue. It is highly dependent on the homogeneity and particle size of the restorative material's microstructure.

Zirconia has a fine, uniform structure; in order to prevent enamel wear, mirror polishing is carried out using appropriate polishing materials and instruments. This is carried out both in the dental laboratory and in the office if occlusal adjustment is required.

Recent studies indicates that monolithic zirconia restorations cause acceptable antagonist enamel wear. Moreover, the results agreed that the final restoration's surface texture plays an essential role in the wear process, but does not influence mechanical performance [65].

Other studies [66, 67] have focused on the comparison of the wear of enamel opposing natural enamel, zirconia, and metal ceramic crowns.

They indicated that the antagonist enamel wear of zirconia was similar to or more than that of natural teeth but less than that of metal-ceramics. Additional properly designed, longer follow-up clinical trials with larger sample sizes are needed to evaluate the antagonist enamel wear of monolithic zirconia crowns in vivo.

Surface Treatment and Cement
The glass can be mordanted with hydrofluoric acid, which greatly increases the surface roughness and thus the micromechanical adhesion potential of the adhesive. In addition, the application of a silane, i.e. a coupling agent, creates a chemical bond between the silicon oxide making up the glass and the organic part of the adhesive.

In the case of polycrystalline ceramics, bonding is problematic due to the ineffectiveness of etching in creating roughness, and the absence of silica for chemical bonding. a number of studies have been carried out to determine which surface pre-treatment and/or bonding material can be used to obtain the best adhesion values for zirconia.

For surface pretreatment, the aim is to obtain a rough, chemically activated ceramic surface [35]. Pretreatments can be grouped into two categories: "conventional" pretreatments such as mechanical abrasion (or milling), air-abrasion (or sandblasting) with alumina, and tribochemical silica coating. In addition, a primer could be applied to increase adhesion. Other "less conventional" treatments, such as electrical discharge machining (or electro-erosion), lasers, selective infiltration etching, porcelain coating (or glazing) and acid treatments, were also used.

Milling permits an increase in roughness through the use of diamond milling cutters. The study by Yegin *et al.*, [36] shows that the advantage of milling is that it induces compressive stresses on the surface, thereby increasing the bond strength of the Y-TZP to the adhesive. A study by Qeblawi *et al.*, [37] shows that this treatment induces an increase in flexural strength, but less than for air-abrasion.

Alumina air-abrasion, or sandblasting, is thus considered the "gold standard" in zirconia surface treatment. It involves the projection of alumina particles with diameters ranging from a few micrometers to 25 to 250µm. This technique eliminates the surface layer of contaminants on the ceramic to improve the wettability of the treated surface, and creates a surface roughness that permits micro-mechanical locking between the ceramic and the adhesive agent [38, 39]. It also increases the flexural strength of zirconia by inducing a tetragonal to monoclinic phase transformation [40, 41]. However, these phase transformations can lead to material fatigue. A study by Zhang *et al.*, in 2004 claimed that sandblasting causes the formation of micro-cracks which diminish the strength of zirconia [42]. However, it would appear that the adhesive diffuses into the microcracks and considerably strengthens the ceramic [43]. Sharp-edged surface, which reduces fracture resistance [44]. Sandblasting should preferably be carried out before sintering A study by d'Okutan *et al.*, [44] revealed that air-abrasion prior to sintering creates rounded edges on the zirconia surface, whereas air-abrasion after sintering forms a sharp-edged surface, which reduces fracture resistance [44].

Tribochemical silica coating involves high-pressure spraying of alumina grains coated with silica. This deposits a layer of silica on the zirconia surface, improving the interaction of the silane with the adhesive. Studies show better bonding results with tribochemical silica coating than with air abrasion [45-48].

Wandscher *et al.*, [49] propose a new tribochemical silica coating technique using feldspathic ceramic powder and leucite-based ceramic powder (glass-ceramic). This pre-treatment would enable higher bond strengths to be achieved with feldspathic ceramic powder than with conventional tribochemical silica coating. However, further studies are required to confirm these results.

Electro-erosion is an unconventional process that creates a desired shape by eroding the material with electric sparks in a dielectric medium (a medium that cannot conduct electric current). With this technique, a high degree of surface roughness is achieved by successive electrical discharges, resulting in higher shear strength values than are obtained with air-abrasion or tribochemical silica coating [50].

The laser is used to increase the surface roughness of zirconia and improve micromechanical retention. Different lasers have been proposed for this use: the Er:YAG laser, the Nd:YAG laser and the CO_2 laser. the Er:YAG laser does not improve the bond strength of the ceramic to the zirconia, whereas pretreatment with the CO_2 laser and the Nd:YAG laser combined with sandblasting, and aging conditions, slightly improves the bond strengths of the zirconia with the [51, 52] adhesive.

The bond strengths obtained are inferior, however, to those obtained with air-abrasion and tribochemical silica coating [53]. New studies are currently focusing on the use of a femtosecond laser. This laser produces ultra-short pulses 62. Microscopic images of the treated surfaces show deep horizontal grooves to enhance retention. Ultrashort lasers have shown the most promising results better than air-abrasion pretreatment with 25µm diameter grains, and tribochemical silica pretreatment.

Glazing consists of fusing a fine layer of glass onto zirconia [54]. Studies show that this technique, followed by hydrofluoric acid etching, significantly improves zirconia bonding compared with more conventional surface pretreatments such as sandblasting and tribochemical silica coating [54, 55]. However, these results are not confirmed by the study of Yang *et al.*, [56], who found that the results were inferior to those of other pretreatments after ageing techniques.

SIE (selective infiltration etching) is a technique based on a heat-induced curing process, which works by applying stresses to the zirconia grain interfaces via two thermal cycles.

In combination, a fine layer of low-melting glass is applied to the surface. The molten glass will selectively infiltrate between the surface grains and allow a rearrangement of the grains, resulting in the creation of a three-dimensional network of porosity between the grains [57]. This technique has a number of advantages over air-abrasion: it is selective and therefore only affects grains directly exposed to the infiltrating agent, enabling better control of the etched zone. In this study by Çakirbay *et al.*, [57], SIE significantly improved bond strength compared with sandblasting. A study by Casucci *et al.*, reported that SIE significantly increased surface roughness without causing degradation of the ceramic. One obstacle to the widespread use of SIE is that it requires more time and delicate handling at each stage of the technique [58, 59].

For acid pretreatment, zirconia is immersed in an acid bath. Several solutions with different compositions are proposed. Their aim is to avoid the impact of alumina particles during air-abrasion of the zirconia surface, while seeking to increase surface roughness. The study by Akay *et al.*, [60] shows that hot chemical bonding, which consists of bathing the zirconia part in a hydrochloric acid and iron chloride bath at 100°C, considerably improves zirconia adhesion compared with air-abrasion, while creating less stress on the zirconia surface. This technique improves surface roughness at the nanometric scale by dissolving the surface grain structure. The advantage of this technique is that it uses lower temperatures than other techniques (laser, EIS, glazing) [61].

To summarize, the most commonly used surface treatments today remain alumina air-abrasion and tribochemical silica coating, with adhesion values showing signs of superiority for the tribochemical treatment. Other promising treatments with good adhesion values are femtosecond laser, electroerosion and selective infiltration etching. The disadvantages of these three treatments lie mainly in their difficulty of application and high cost. Hot chemical etching also offers a number of advantages, but this approach has yet to be explored due to a lack of consensus.

Finally, primers are used to reduce the surface tension of the substrate, thereby increasing the wettability of the adhesive. Silanisation is only effective in the presence of silica on the ceramic surface. For surfaces sandblasted with alumina, coupling agents based on methacrylate functional monomers are proposed, and for surfaces pre-treated with tribochemical silica, silanes are used as the coupling agent and bond to the silica particles retained in the zirconia. However, as the silica coating is not uniform, the silane can only be effective on a small part of the zirconia surface. To counter this weak bonding of the silane to the zirconia, ethanol-based silanes and phosphate-based coupling agents were introduced. This chemical conditioning improves adhesion values.

Adhesives can be classified into three groups: those containing MDP, those containing functional monomers without MDP and those without functional monomers. A 2018 systematic literature review shows

that adhesives containing MDP provide better bond strengths (Panavia F2.0, Panavia SA, Panavia SA Plus) than the other two categories [63].

We can therefore conclude that the main element for chemical adhesion is the use of MDP monomer, whether it is included in the primer or directly in the bonding material. However, it would appear that a conventional adhesive combined with a primer containing MDP is more effective than using an adhesive containing MDP directly. For high-translucent zirconia [64]. The available evidence suggests that resin bonding protocols successfully applied to conventional zirconia are also the most successful for high-translucent zirconia.

CONCLUSION

New generations of zirconia have higher translucency but this is generally associated with the side effect of lower strength. Therefore, an increase in translucency cannot always be considered to be advantageous. In the case of colored tooth stumps in particular, a reduced masking potential of the restoration can also be a negative result. It is important, therefore, to select and use the correct material according to the range of indications.

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