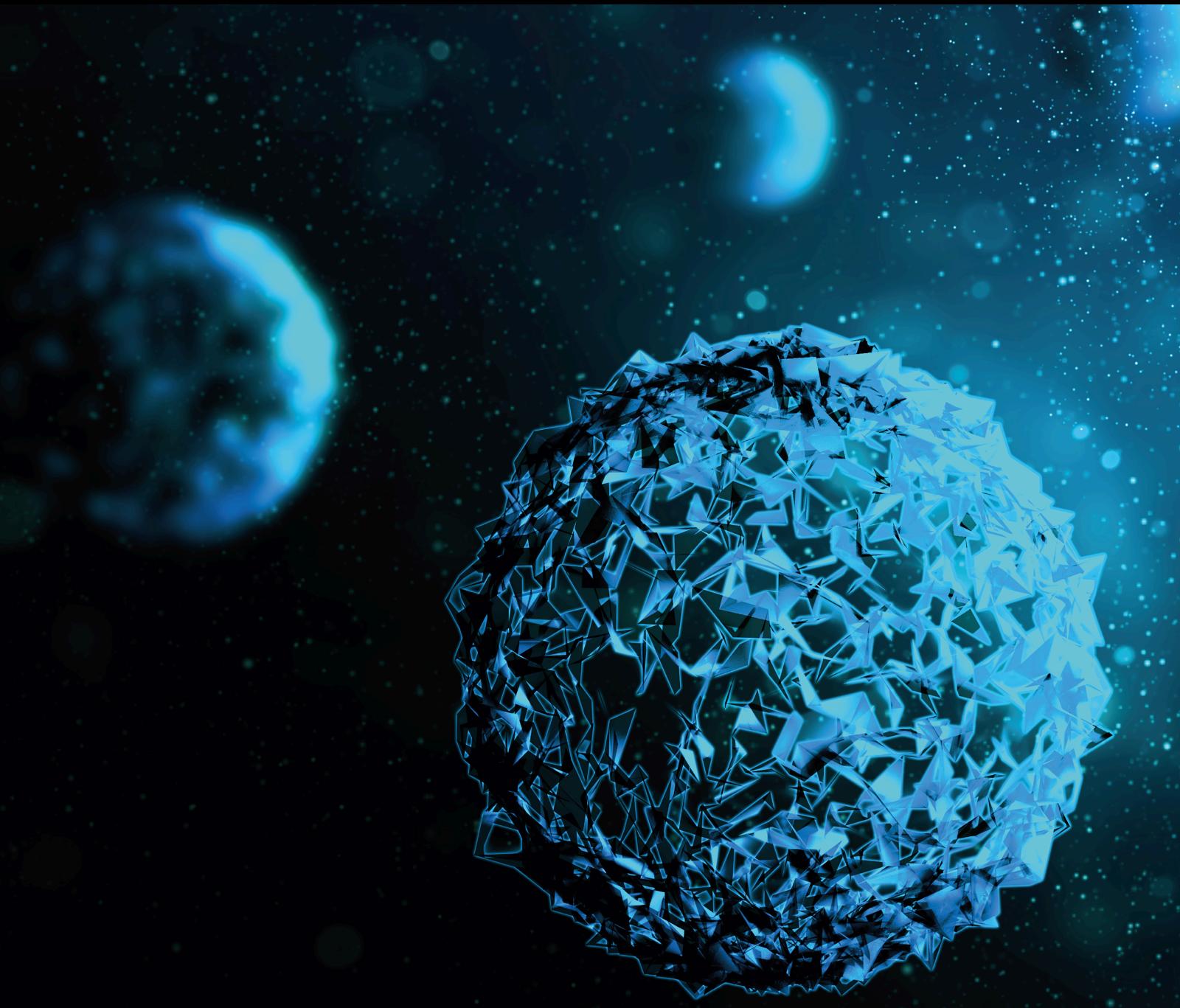


# Novel Zirconia in Dentistry: Clinical Applications and Challenges

Lead Guest Editor: Hao Yu

Guest Editors: James Kit Hon Tsoi and Chang-yuan Zhang





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## Corrigendum

# Corrigendum to “Determination of Hardness and Fracture Toughness of Y-TZP Manufactured by Digital Light Processing through the Indentation Technique”

**Ziyu Mei , Yuqing Lu , Yuxin Lou , Ping Yu , Manlin Sun , Xin Tan ,  
Junjing Zhang , Li Yue , and Haiyang Yu **

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Received 20 April 2021; Accepted 20 April 2021; Published 3 May 2021

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In the article titled “Determination of Hardness and Fracture Toughness of Y-TZP Manufactured by Digital Light Processing through the Indentation Technique” [1], incorrect images were used for Figures 1 and 2 due to an error during the preparation of the manuscript. Figures 1 and 2 should be corrected as follows:

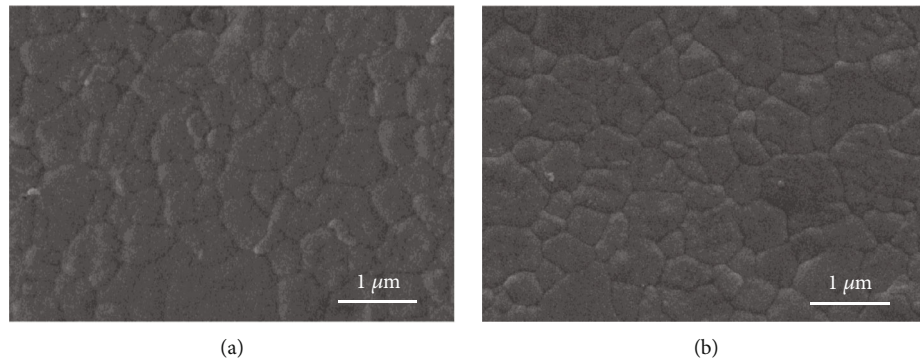


FIGURE 1: SEM images of the zirconia surface of the (a) DLP group and (b) MILL group at magnification  $\times 40\text{k}$  and  $\times 20\text{k}$ .

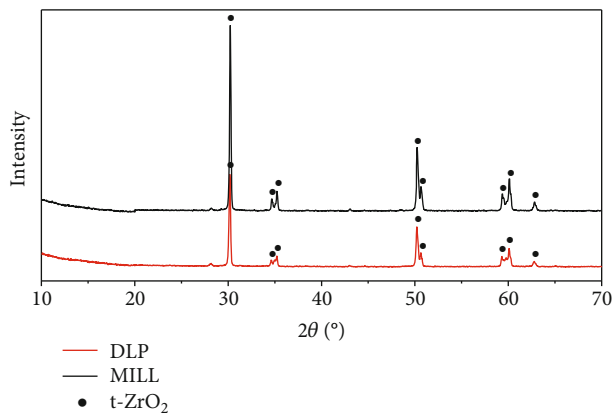


FIGURE 2: XRD patterns of zirconia.

## References

- [1] Z. Mei, Y. Lu, Y. Lou et al., "Determination of Hardness and Fracture Toughness of Y-TZP Manufactured by Digital Light Processing through the Indentation Technique," *BioMed Research International*, vol. 2021, Article ID 6612840, 11 pages, 2021.

## Research Article

# Determination of Hardness and Fracture Toughness of Y-TZP Manufactured by Digital Light Processing through the Indentation Technique

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Received 1 December 2020; Revised 9 January 2021; Accepted 18 January 2021; Published 13 February 2021

Academic Editor: James Kit Hon Tsoi

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**Objective.** The purpose of the study was to determine the hardness and fracture toughness of dental yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) manufactured by digital light processing (DLP) technology to study its clinical prospects. **Methods.** The experimental group was DLP-manufactured zirconia, and the control group was milled zirconia. The hardness was investigated under a range of test loads (0.49 N, 0.98 N, 1.96 N, 4.90 N, 9.81 N, 29.42 N, 49.03 N, 98.07 N, and 196.1 N). Meyer's law was applied to describe the indentation size effect (ISE). Meanwhile, the PSR model and MPSR model were utilized to generate true hardness values. The cracks were observed to be induced by indentation under loads above 49.03 N, while the cracks showed the radial-median type under the load of 196.1 N, under which the fracture toughness was calculated. **Results.** The true hardness of DLP-manufactured zirconia was 1189 HV based on the PSR model and 1193 HV based on the MPSR model, a bit lower than that of milled zirconia. The fracture toughness was  $3.43 \pm 0.29 \text{ MPa}\sqrt{\text{m}}$ , which showed no statistical difference with the milled zirconia. **Conclusion.** The dental zirconia manufactured by the DLP 3D printing technique is similar to that manufactured by the conventional milling process in hardness and fracture toughness, thus having a promising future of clinical use.

## 1. Introduction

In recent years, yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) is widely used in dentistry due to its excellent biocompatibility and mechanical properties, as well as its satisfying aesthetics. Usually, the zirconia prostheses are manufactured by the numerically controlled milling process, while there still exist some problems [1]. Firstly, the milling process is a subtractive operation from a presintered or fully sintered disc, which results in a massive waste of material. Secondly, the prostheses with fine structures such as deep fossae or grooves usually could not be shaped accurately, limited by the burs with certain diameters [2]. Thirdly, when milling the zirconia restorations with thin wall thickness, the process may cause mechanical damage due to the bur vibration [3].

With the rapid development of three-dimensional (3D) printing techniques, 3D printing ceramics becomes a hot issue in prosthodontics. This technique builds parts layer by layer with no need for machining or mould, thus possessing the characteristics of high production efficiency, high usage rate of material, and unlimited printing shapes [4]. Therefore, the 3D printing technique could be a potential alternative approach to manufacturing restorations with fine structures. Among the 3D printing techniques, the digital light processing (DLP) technique is relatively mature in ceramic forming. The DLP technique firstly forms green parts through light curing the resins in ceramic slurry [5]. Then, posttreatments involving debinding and final sintering are performed to obtain the dense ceramic parts. Compared to other 3D printing techniques, the DLP technique has

TABLE 1: Group names, components, and manufacturers of zirconia.

Group	Material	Components (mass%)	Manufacturer
DLP	Y-TZP slurry (solid content with 58 vol%)	ZrO <sub>2</sub> +HfO <sub>2</sub> +Y <sub>2</sub> O <sub>3</sub> (99.72)	QuickDemos Company (China)
		Y <sub>2</sub> O <sub>3</sub> (5.22)	
		Al <sub>2</sub> O <sub>3</sub> (0.24)	
		Remaining (0.04)	
MILL	Presintered Y-TZP disc (Zenostar MO)	ZrO <sub>2</sub> +HfO <sub>2</sub> +Y <sub>2</sub> O <sub>3</sub> (≥99.0)	Ivoclar Vivadent (Liechtenstein)
		Y <sub>2</sub> O <sub>3</sub> (4.5~6.0)	
		Al <sub>2</sub> O <sub>3</sub> (≤1.0)	
		Remaining (≤5.0)	

advantages in forming small objects with high accuracy requirements, considered to be a preferred technique for 3D printing dental zirconia prostheses [6].

At present, there were a few studies on the mechanical properties of dental zirconia manufactured by 3D printing techniques. Lu et al. investigated that DLP-manufactured zirconia can achieve high flexural strength close to milled zirconia [7]. Li et al. printed the zirconia bridges and implants by stereolithography and displayed the defects in printed objects [6]. Osman et al. prepared zirconia implants based on the DLP technique, which achieved relatively high accuracy, surface quality, and flexural strength [8]. However, there is still a lack of studies on the hardness and fracture toughness of DLP-manufactured zirconia. Hardness is defined as the ability to resist plastic deformation, indicating the ease of surface polishing or scratching [9], which may have an impact on the aesthetic properties of zirconia prostheses. Fracture toughness describes the resistance ability to crack propagation under loading [9]. Thus, in this study, the dental zirconia manufactured by the DLP 3D printing technique was investigated and compared with milled zirconia to provide a further theoretical basis for its clinical use. The null hypothesis was that there was no statistical difference in the hardness and fracture toughness between DLP-manufactured zirconia and milled zirconia.

## 2. Materials and Methods

**2.1. Specimen Preparation.** All experiments were performed on zirconia discs with dimensions of diameter 20.0 mm and thickness 2.0 mm. The control group was Y-TZP, which was milled out of presintered Y-TZP discs (Zenostar, Ivoclar Vivadent, Liechtenstein) by a CAD/CAM machine (Wieland Zenostar mini, Ivoclar Vivadent, Liechtenstein) (MILL group). The experimental group was Y-TZP manufactured by a DLP stereolithography printing machine (Ceramatrix, QuickDemos Company, China) (DLP group), as is listed in Table 1. The zirconia slurry for printing was composed of 58 vol% Y-TZP powder and photocurable monomers. Firstly, the green parts of the DLP group were printed layer by layer under a light intensity of 90 mW/cm<sup>2</sup> with 25 μm each layer. Then, the debinding process was performed by putting the green parts into the debinding furnace under 100-450°C to remove organic parts. At last, the final sintering process was carried out on Y-TZP of the two groups by sintering

them for 2 h at 1510°C with heating and cooling rates set at 300°C/h. All samples were observed under an optical microscope, and those without surface defects were selected for experiments. Before experiments, the samples were firstly ground with P400-P1200 SiC abrasive paper, followed by a polishing step with 9 μm-1 μm polishing slurry in a polishing machine (Struers, Copenhagen, Denmark).

**2.2. Characterization of the Specimens.** To characterize the specimens, the density, grain size, crystalline phase, and Young's modulus were investigated. The density was measured by means of Archimedes' method using the calculation

$$d = \frac{m_1 \times \rho}{m_3 - m_2}, \quad (1)$$

where  $d$  is the density (g/cm<sup>3</sup>),  $m_1$  is the mass of the dried specimen in air (g),  $m_2$  is the mass of the water-impregnated specimen in water (g),  $m_3$  is the mass of the water-impregnated specimen (g), and  $\rho$  is the density of water which equals to 0.9982 g/cm<sup>3</sup>. The surface morphologies of Y-TZP were observed by a scanning electron microscope (SEM, Inspect F, USA). And the SEM images were used for analyzing the grain sizes using software ImageJ 1.52a (National Institutes of Health, USA). The crystalline phase structure was determined by an X-ray diffractometer (XRD, Empyrean, Netherlands), with a step size of 0.02° and a scan range of 10°-70°. Young's modulus was tested by an MHT<sup>3</sup> microindentation tester. The maximum load was 10 N, and the holding time was 10 s. Young's modulus of each group was calculated by Indentation Software.

**2.3. Hardness Measurements.** According to ASTM C1327-2015 [10], the Vickers hardness was measured using a hardness tester (Zuanshi, China) under the following loads: 0.49 N (HV0.05), 0.98 N (HV0.1), 1.96 N (HV0.2), 4.90 N (HV0.5), 9.81 N (HV1), 29.42 N (HV3), 49.03 N (HV5), 98.07 N (HV10), and 196.1 N (HV20). There were 3 specimens for each group under each load, and 10 indentations were randomly made on each specimen with a dwelling time of 15 s. The Vickers hardness was calculated by the following expression:

$$HV = \frac{\alpha F}{d^2}, \quad (2)$$

TABLE 2: The density, grain size, and crystalline phase structure of zirconia.

Group	Density (g/cm <sup>3</sup> )		Relative density (%)	Grain size (μm)		Crystalline phase structure	Young's modulus (GPa)	
	Mean	SD		Mean	SD		Mean	SD
DLP	6.0198	0.0213	99.0099	0.6030	0.0326	Tetragonal	221.4	2.2
MILL	6.0382	0.0115	99.3125	0.5911	0.0330	Tetragonal	225.1	3.4

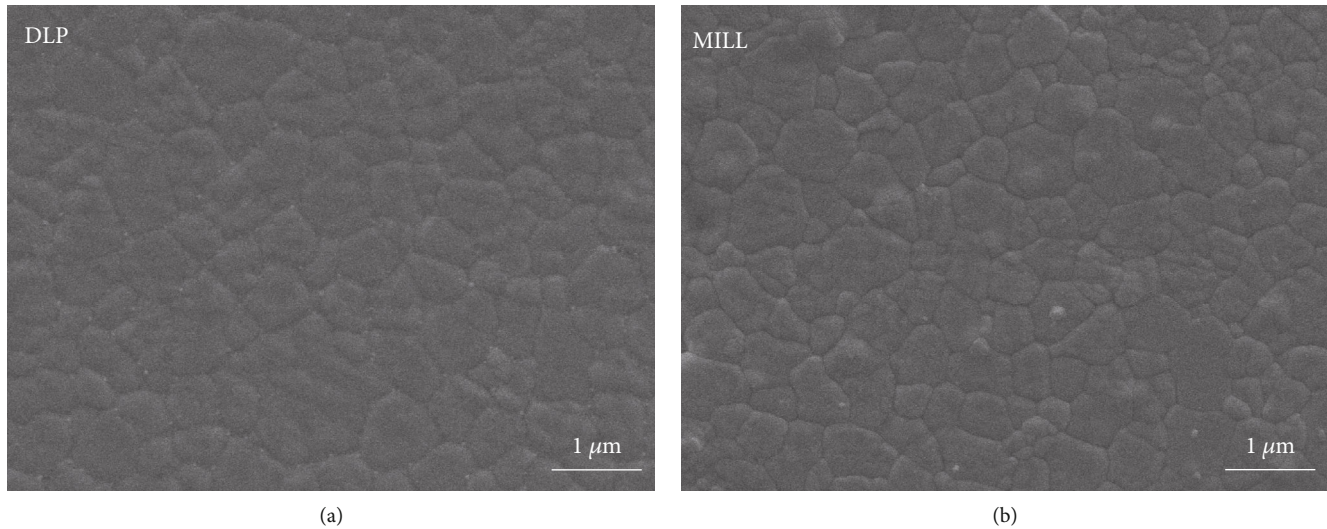


FIGURE 1: SEM images of the zirconia surface. (a) DLP group. (b) MILL group.

where HV is the Vickers hardness (HVn),  $F$  is the applied load (N),  $d$  is the mean value of the indentation diagonals (mm), and  $\alpha$  is the indenter's geometrical constant, which equals 0.1891.

**2.4. Fracture Toughness Measurements.** The fracture toughness was measured using the indentation fracture method. Based on the Vickers hardness tests above, the length of the crack induced by the indentation  $c$  (mm) and half of the indentation diagonal  $a$  (mm) were measured to calculate the  $c/a$  ratio. The crack type could thus be confirmed [11]. When  $c/a > 2.5$ , the crack shows the Palmqvist type, and when  $c/a < 2.5$ , the crack shows the radial-median crack type. The fracture toughness values were then calculated using the correct equation for the corresponding crack type.

### 3. Result

**3.1. Microstructural Characterization.** As is shown in Table 2, there was no statistical difference between the two groups in density and grain size. The grains of both groups were of tight arrangement with uniform size (see Figure 1). The XRD pattern in Figure 2 shows that only the tetragonal phase was found in the two groups of zirconia. Young's modulus was  $221.4 \pm 2.2$  GPa and  $225.1 \pm 3.4$  GPa separately for the DLP group and the MILL group.

**3.2. Apparent Hardness.** The average hardness values versus applied indentation loads are plotted in Figure 3. It is

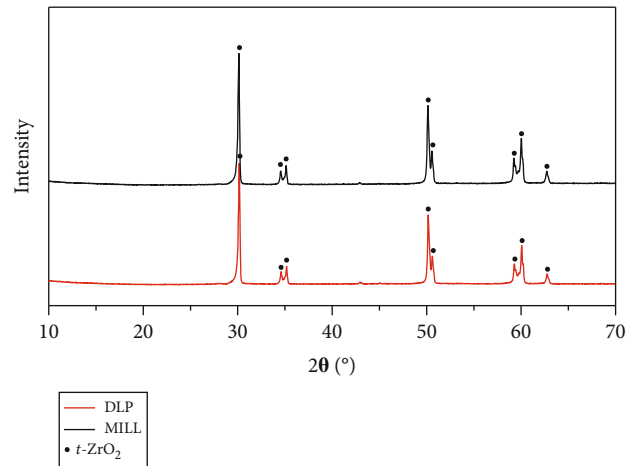


FIGURE 2: XRD patterns of zirconia.

observed that the hardness value HV decreased with the increasing indentation load  $F$ , which is called the normal indentation size effect (ISE) [12]. To verify the ISE, Meyer's law was applied [13]:

$$F = K \cdot d^n, \quad (3)$$

where  $F$  is the load (N),  $K$  is a hardness constant, and  $d$  is the mean value of the indentation diagonal (mm). A linear regression analysis was conducted on  $\ln F$  versus  $\ln d$  to



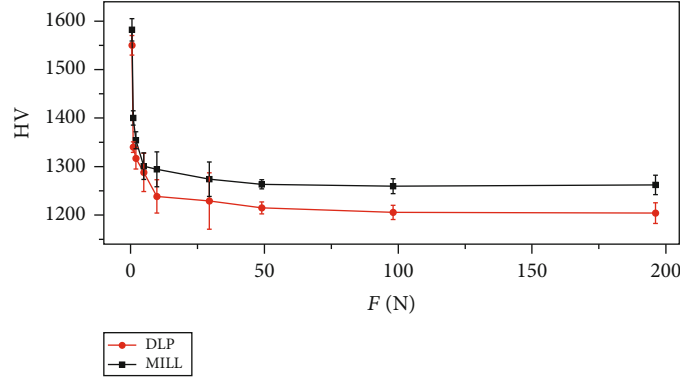


FIGURE 3: Plot of variations in hardness versus applied load. The error bars represent the standard deviation of hardness values of 30 indentations under each applied load.

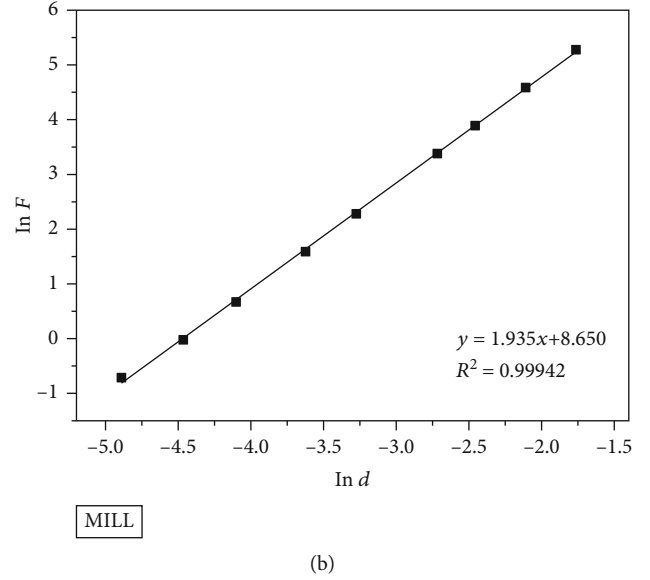
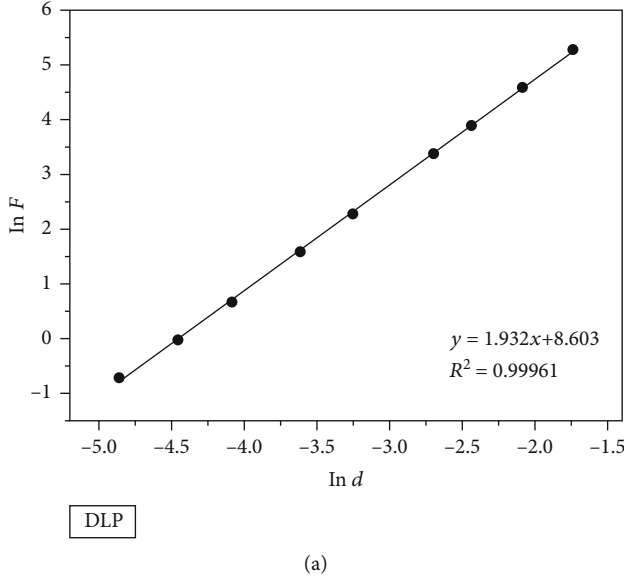


FIGURE 4: Fitting curves of  $\ln F$  versus  $\ln d$  based on Meyer's law. (a) DLP group. (b) MILL group.

obtain the slope that represents Meyer's index  $n$ . The fitting curves are displayed in Figure 4. As is given in Table 3, Meyer's index was  $1.935 \pm 0.011$  for the DLP group and was  $1.947 \pm 0.011$  for the MILL group, both of which were smaller than 2, further confirming the normal ISE behavior of zirconia. Therefore, the obtained hardness values were apparent hardness dependent on the applied load; thus, two more empirical models were used to determine the true hardness.

**3.3. True Hardness.** The proportional specimen resistance (PSR) model and the modified proportional specimen resistance (MPSR) model were used to determine the true hardness. The PSR model is a modification of Meyer's law [14], and it explains the relation between the load and the indentation diagonal. The expression is as follows:

$$F = a_1 \cdot d + a_2 \cdot d^2, \quad (4)$$

TABLE 3: The fitting results of Meyer's law.

Group	$n$	$\ln K$	$K \text{ (N mm}^{-n}\text{)}$	$R^2$
DLP	$1.932 \pm 0.013$	$8.603 \pm 0.044$	5447.979	0.99961
MILL	$1.935 \pm 0.016$	$8.650 \pm 0.056$	5710.147	0.99942

where  $a_1 \text{ (N mm}^{-1}\text{)}$  is a constant related to elasticity and  $a_2 \text{ (N mm}^{-2}\text{)}$  is a constant related to plasticity. These two values were calculated by linear regression carried out on  $F/d$  versus  $d$  (see Figure 5). The results are presented in Table 4.

The MPSR model is developed based on the PSR model [15, 16], which adds a coefficient  $a_0 \text{ (N)}$  related to the material characterization and surface treatment:

$$F = a_0 + a_1 \cdot d + a_2 \cdot d^2. \quad (5)$$

Polynomial regression was applied to  $F$  versus  $d$  to obtain

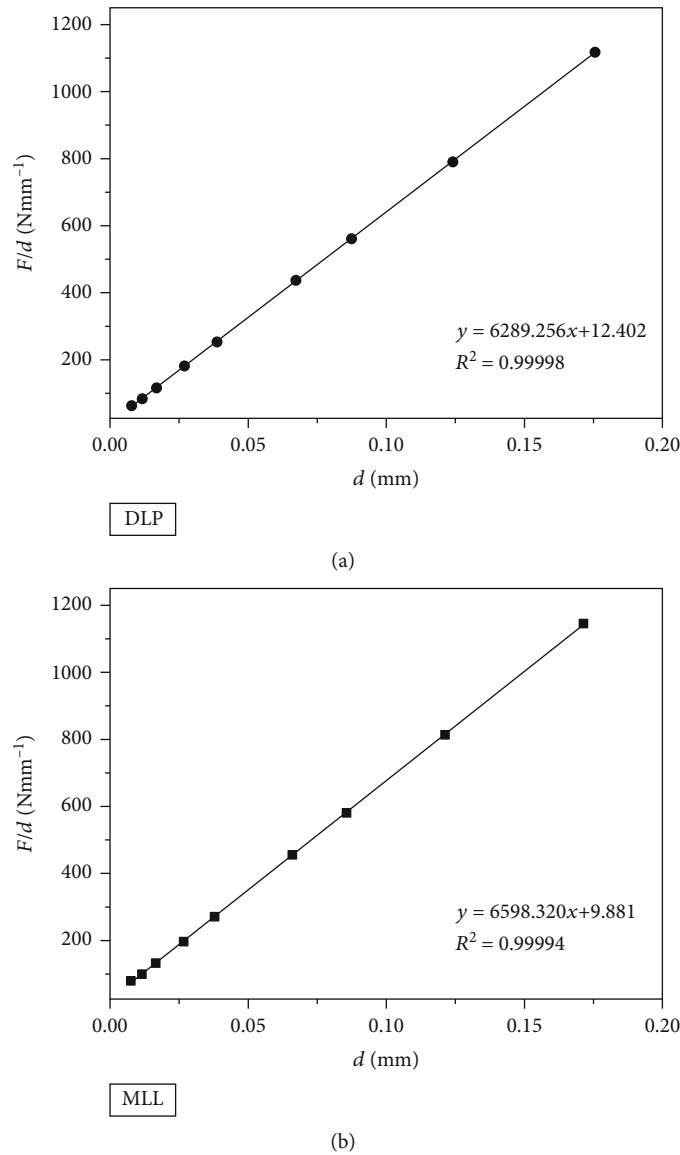


FIGURE 5: Fitting curves of  $F/d$  versus  $d$  based on the PSR model. (a) DLP group. (b) MILL group.

TABLE 4: The fitting results of the PSR model.

Group	$a_1$ (N mm <sup>-1</sup> )	$a_2$ (N mm <sup>-2</sup> )	$R^2$
DLP	$12.402 \pm 0.823$	$6289.256 \pm 9.995$	0.99998
MILL	$9.881 \pm 1.513$	$6598.320 \pm 18.783$	0.99994

$a_0$ ,  $a_1$ , and  $a_2$  (see Figure 6), and the results are displayed in Table 5. The true hardness  $HV_T$  (HV) could be calculated by the following equation [15, 16]:

$$HV_T = \alpha \cdot a_2. \quad (6)$$

As is shown in Table 6, the true hardness was 1189 HV for the DLP group and 1248 HV for the MILL group based on the PSR model and was 1193 HV for the DLP group and 1261 HV for the MILL group based on the MPSR model.

**3.4. Fracture Toughness.** According to the measurements of crack length  $c$  (mm) and half of the indentation diagonal  $a$  (mm), the  $c/a$  ratio was calculated to be smaller than 2.5 under the load of 49.03 N and larger than 2.5 under the load of 196.1 N, while under the load of 98.07 N, the  $c/a$  ratio showed a mixture type (see Figure 7). The fracture toughness value was calculated under the load of 196.1 N since it could generate clearly visible cracks of radial-median type, whereas the Palmqvist cracks noted at 49.03 N were not that clear. Therefore, the model developed by Anstis et al. [17] for the radial-median crack type was selected for the calculation of fracture toughness  $K_{IC}$  (MPa√m):

$$K_{IC} = 0.016 \times \frac{F}{c^{1.5}} \times \left( \frac{E}{HV} \right)^{0.5}, \quad (7)$$

where  $HV = 1.8544 \times (F/(2a)^2)$  (MPa),  $c$  is the crack length

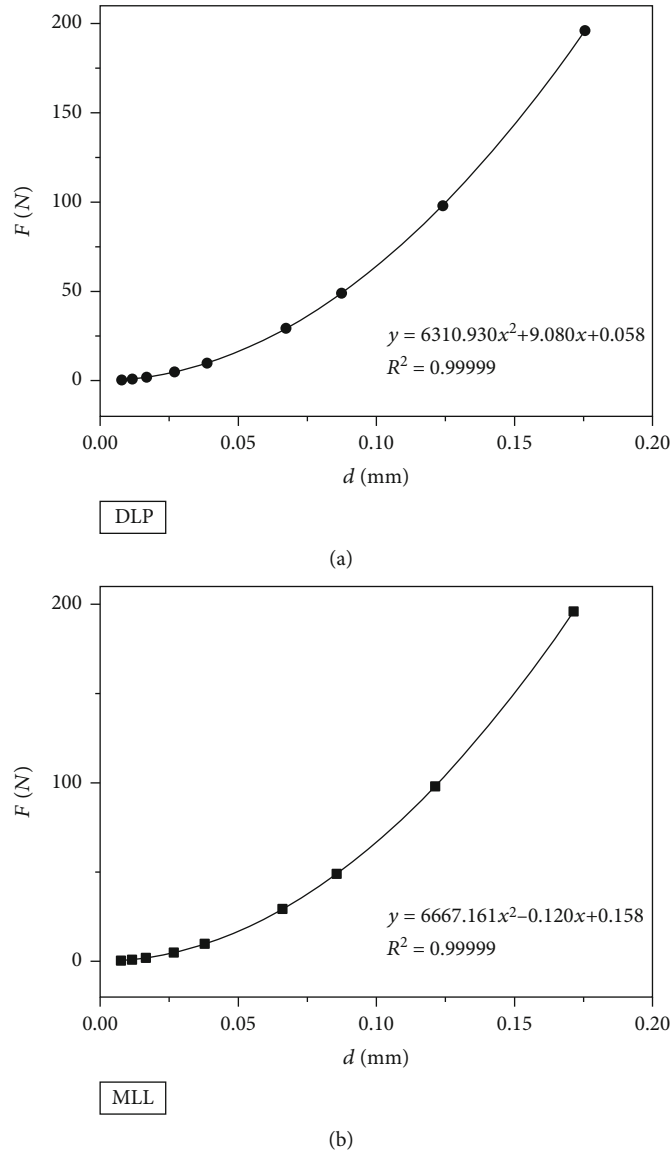


FIGURE 6: Fitting curves of  $F$  versus  $d$  based on the MPSR model. (a) DLP group. (b) MILL group.

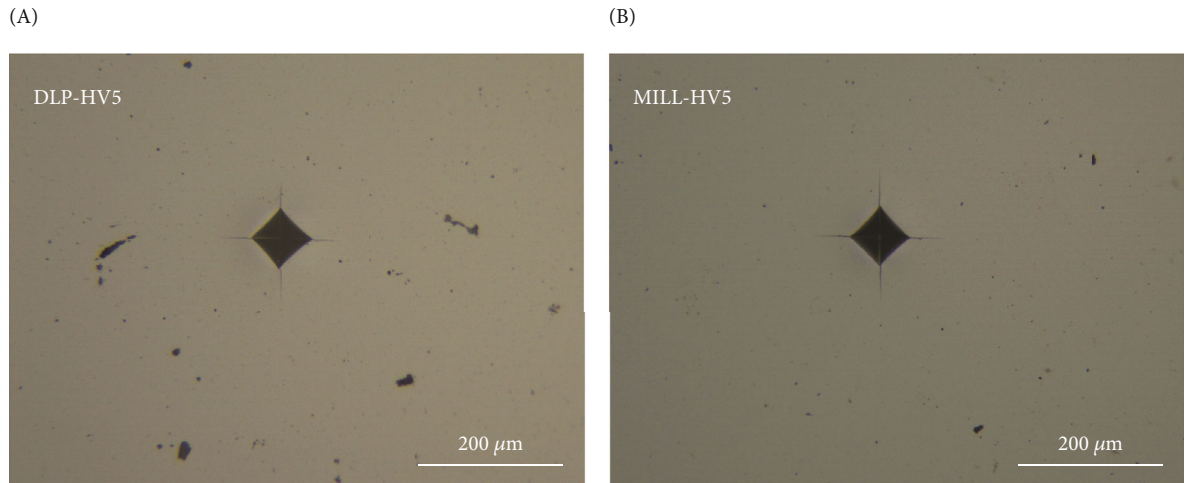
TABLE 5: The fitting results of the MPSR model.

Group	$a_0$ (N)	$a_1$ (N mm <sup>-1</sup> )	$a_2$ (N mm <sup>-2</sup> )	$R^2$
DLP	$0.058 \pm 0.081$	$9.080 \pm 2.630$	$6310.930 \pm 14.719$	0.99999
MILL	$0.158 \pm 0.105$	$-0.120 \pm 3.486$	$6667.161 \pm 19.962$	0.99999

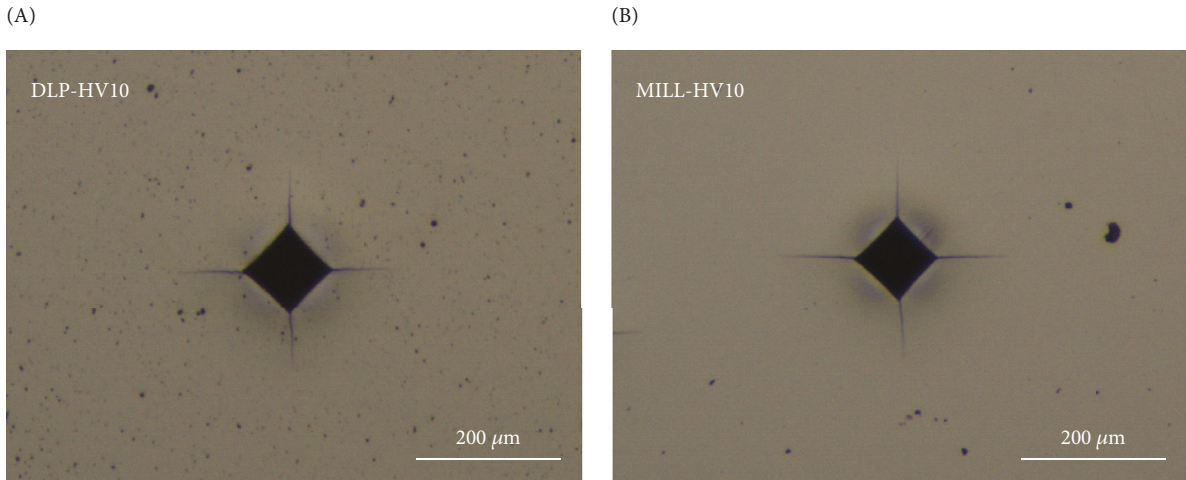
TABLE 6: True Vickers hardness of the two groups of zirconia.

Group	PSR (HV)	MPSR (HV)
DLP	1189	1193
MILL	1248	1261

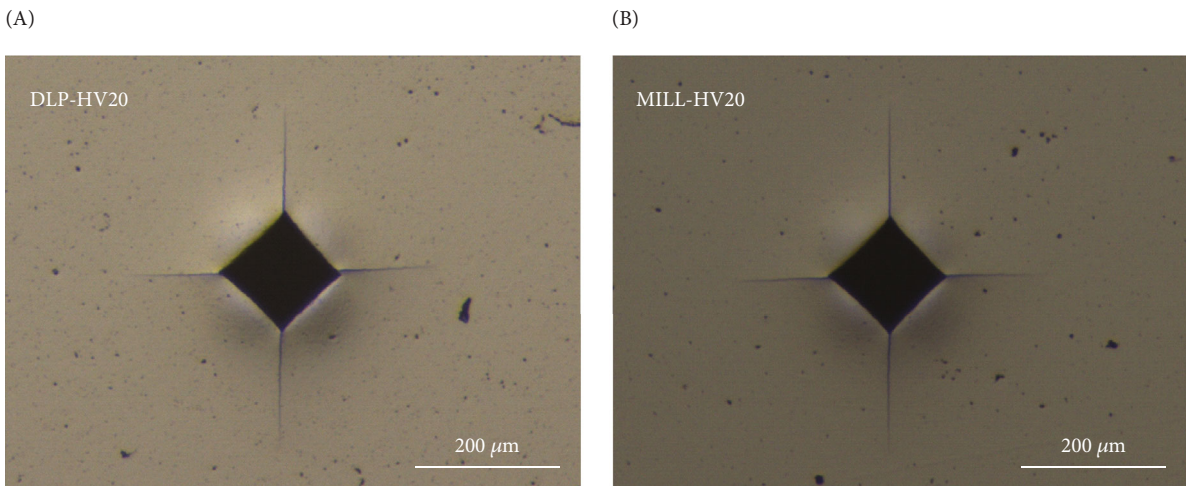
from the indentation center to the crack tip (mm), and  $E$  is Young's modulus of zirconia (GPa). The fracture toughness value was  $3.43 \pm 0.29$  MPa $\sqrt{m}$  for the DLP group and  $3.44 \pm 0.23$  MPa $\sqrt{m}$  for the MILL group. Student's  $t$ -test was conducted using the SPSS 22.0 software (IBM, Armonk, USA) to analyze the difference in  $K_{IC}$  values between the two groups. The results indicated that there was no significant difference between DLP-manufactured zirconia and milled zirconia ( $P > 0.05$ ). The indentation crack profiles of both groups are shown in Figure 8. Cracks of both groups



(a) Indentations under the load of 49.03 N.  
The cracks were of Palmqvist type; some of which could not be observed clearly



(b) Indentations under the load of 98.07 N.  
The cracks were of Palmqvist type or radial-median type



(c) Indentations under the load of 196.1 N.  
The cracks were of radial-median type, which were clearly visible

FIGURE 7: Optical micrographs of Vickers indentations with cracks emanating from the indentation corner under loads of 49.03 N (a), 98.07 N (b), and 196.1 N (c).



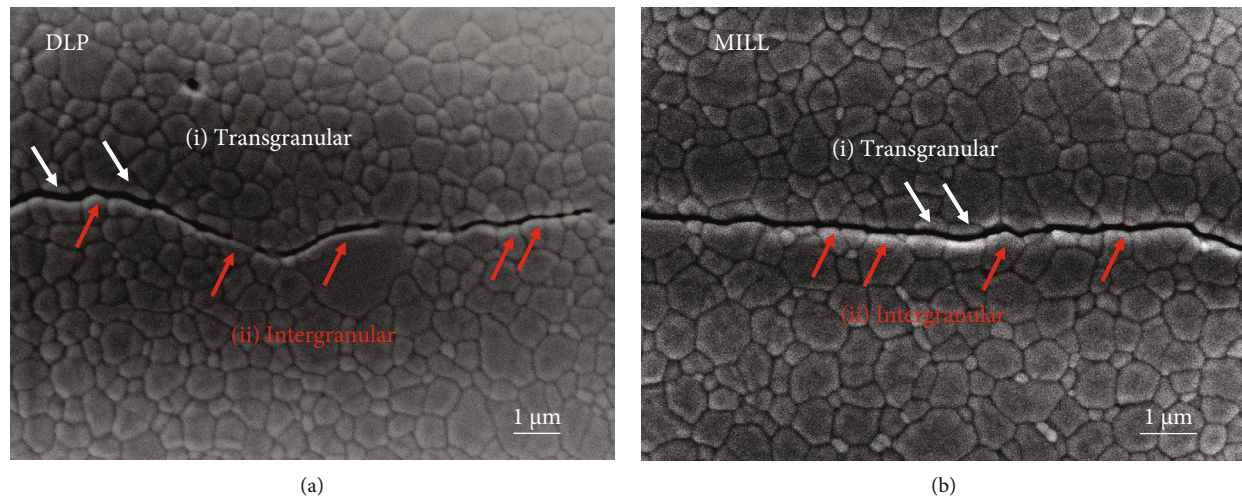


FIGURE 8: Indentation crack profiles. (a) DLP group. (b) MILL group. The cracks of both groups showed a mixture fracture mode of intergranular fracture (i) and transgranular fracture (ii).

presented a mixture fracture mode of intergranular mode in the predominant role and transgranular mode.

#### 4. Discussion

The results of this study show that the Vickers hardness of DLP-manufactured zirconia was statistically lower than that of milled zirconia while there was no statistical difference in fracture toughness between two groups of zirconia, thus rejecting the null hypothesis.

In this study, the dental zirconia specimens were manufactured by two techniques. Since the 3D printing zirconia slurry used in this study was 3 mol% yttria partially stabilized tetragonal zirconia polycrystal (3Y-TZP), which is composed of similar contents to the commercial nontransparent zirconia (Table 1), the Zenostar MO presintered Y-TZP discs were chosen as the material of the control group. Besides the similar composition contents, the same final sintering procedure was selected to densify the parts of both groups. Thus, the main difference was in the forming of the parts before the final sintering. As for the numerically controlled milling technique, the zirconia green body is shaped by isostatic cold pressing, followed by a presintering procedure to achieve a certain strength [18]. Regarding the DLP 3D printing technique, the green body is printed by curing the photosensitive ceramic slurry through light projection; then, the debinding process is carried out to remove the organic parts [19]. The results of microstructural characterization showed that the density, grain size, and phase composition of the two groups were similar to each other, indicating that the difference in forming the parts before the final sintering almost had no influence on the microstructure of zirconia. To some extent, it can be predicted that the mechanical properties including hardness and fracture toughness of zirconia manufactured by the two techniques would be close [20].

The hardness and fracture toughness of the DLP-manufactured zirconia were determined by the indentation technique, which is a standard method for determining the

Vickers hardness [10] while not the recommended method for testing fracture toughness [21]. However, the indentation fracture method is a rather popular technique due to its ease and convenience of operation since the  $K_{IC}$  values could easily be calculated according to empirical formulas based on the results of Vickers indentation tests. Although the  $K_{IC}$  values determined by the indentation fracture method could just be used as approximations of true fracture toughness values, they were good indicators for comparing the fracture toughness between two materials.

The hardness was tested under a range of loads from 0.49 N to 196.1 N. The results revealed that both groups of zirconia had normal ISE, which was further verified by Meyer's law, indicating that the obtained results of hardness were apparent hardness dependent on the applied loads. The apparent hardness of DLP zirconia was a bit statistically lower than that of MILL zirconia for 2% at 0.49 N, 4% at 0.98 N, 3% at 1.96 N, 1% at 4.9 N, 4% at 9.81 N, 4% at 29.42 N, 4% at 49.03 N, 4% at 98.07 N, and 5% at 196.1 N. The PSR model and MPSR model were applied to obtain the true hardness, and the results showed that the true hardness of DLP zirconia was 5% lower than that of MILL zirconia. Research has shown that the Vickers hardness has a strong dependence on porosity and pore size [22]. The hardness would decrease with increasing porosity and pore size. From the SEM images of polished surfaces of zirconia (see Figure 9), pores with diverse shapes and sizes could be observed in the DLP group, while agglomerates with uniform sizes were observed in the MILL group. For the DLP group, the pores tend to form during the coating process when the solid content of the slurry is too high, which leads to high viscosity [23]. And the forming of agglomerates is mostly due to the unstable suspension containing irregular aggregates of particles [24]. With regard to the MILL group, the formation of pores and aggregates may be related to the quality of the raw material powder. The study has also shown that the pores are often concentrated near the surface of the additive manufactured zirconia produced by horizontal building, and

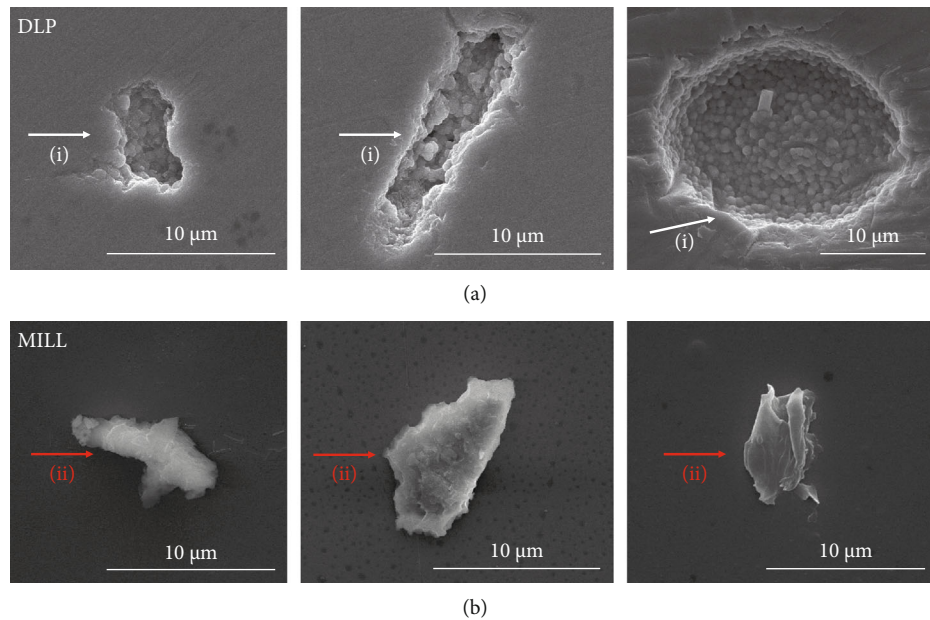


FIGURE 9: SEM images of polished surfaces. (a) DLP group with (i) pores of diverse shapes and sizes. (b) MILL group with (ii) aggregates of uniform sizes.

such defects on the surface of the tensile side would easily become the areas of stress concentration under the applied load, resulting in the failure of the specimens [25]. Although the relative densities of both groups were close to each other, the pores of the DLP group were mainly concentrated near the surface, while those of the MILL group were distributed throughout the entire volume. Therefore, the pores with large sizes on the surface of DLP zirconia might lead to its slightly lower Vickers hardness value.

Zirconia stands out from other ceramics mainly due to its high fracture toughness, which is an important property for the clinical use of bridge frameworks, especially those with large spans. It differs from other brittle ceramic materials in that it would just generate clear indentations with cracks under large loads like metal materials do without any fracture or chipping [26]. The toughening mechanism of zirconia is due to the stress-induced phase transformation. To be specific, when zirconia is subjected to a high load with fracture cracks emanated, the tetragonal phase stabilized at room temperature would transform to the monoclinic phase, causing 3%-5% of volume expansion, which generates compressive stress to prevent cracks from propagation. There was no statistical difference found in the fracture toughness values of both groups, and the main reason for that might be the highly similar microstructure characterization of the two groups of zirconia. As is known, the fracture toughness is mainly dependent on the grain size and grain boundary, which determine the energy required for the crack extension. The higher the energy is required, the higher the fracture toughness is. The XRD pattern showed that DLP zirconia and MILL zirconia have the same phase composition, and the SEM images displayed that the grain arrangement of both groups was even and dense with similar size, thus explaining the results of fracture toughness measurements. However, the  $K_{IC}$  values of zirconia were a bit lower than those of pre-

vious research studies [27, 28], which may be attributed to the difference among the different empirical formulas. A study has shown that the fracture toughness value calculated by the Anstis model was relatively lower than that calculated by other empirical models [11]. Although the indentation fracture method could not be used as a standard method or quantitative determination for the evaluation of ceramic fracture toughness [29], it is a relatively easy and effective method for comparing two materials.

Based on the previous research on the flexural strength of DLP-manufactured Y-TZP [7], this study further investigated its hardness and fracture toughness to achieve a comprehensive understanding of the basic mechanical properties compared to commercial milled Y-TZP. The limitation of this study is that the indentation fracture method used to determine the fracture toughness is not the standard method recommended in the ISO 6872 [21]. The  $K_{IC}$  values calculated by empirical formulas relying on indentation crack lengths could not be used as the true values of fracture toughness. Meanwhile, the dynamic mechanical properties like fatigue property and degeneration behavior need to be studied, and the biocompatibility, printing accuracy, and aesthetic performance also deserve exploration to provide an all-rounded theoretical basis for the clinical application of DLP-manufactured dental Y-TZP.

## 5. Conclusion

According to the study above, the following conclusions can be drawn:

- (1) The DLP-manufactured zirconia is similar to milled zirconia in microstructure, including density, grain size, and crystalline phase composition

- (2) The true hardness of DLP-manufactured zirconia is 5% lower than that of milled zirconia, which may be attributed to the existence of large pores on the surface of DLP zirconia
- (3) There is no statistical difference in fracture toughness between DLP-manufactured zirconia and milled zirconia, which may be due to the highly similar microstructure of both groups of zirconia
- (4) DLP-manufactured dental zirconia can achieve the requirements of dental prostheses in basic mechanical properties

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare there are no conflicts of interest regarding the publication of this paper.

## Acknowledgments

The authors gratefully thank the QuickDemos company for supplying the DLP 3D printing machine and Y-TZP slurry. This study is supported by the National Natural Science Foundation of China (No. 81771113) and the Horizontal Project of Sichuan University (No. 20H0866).

## References

- [1] A. R. Alao, R. Stoll, X. F. Song et al., "Surface quality of yttria-stabilized tetragonal zirconia polycrystal in CAD/CAM milling, sintering, polishing and sandblasting processes," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 65, pp. 102–116, 2017.
- [2] R. Li, H. Chen, Y. Wang, Y. Zhou, Z. Shen, and Y. Sun, "Three-dimensional trueness and margin quality of monolithic zirconia restorations fabricated by additive 3D gel deposition," *Journal of Prosthodontic Research*, vol. 64, no. 4, pp. 478–484, 2020.
- [3] R. Luthardt, M. Holzthuter, H. Rudolph, V. Herold, and M. H. Walter, "CAD/CAM-machining effects on Y-TZP zirconia," *Dental Materials*, vol. 20, no. 7, pp. 655–662.
- [4] M. Dehurtevent, L. Robberecht, J. C. Hornez, A. Thuault, E. Deveaux, and P. Behin, "Stereolithography: a new method for processing dental ceramics by additive computer-aided manufacturing," *Dental Materials*, vol. 33, no. 5, pp. 477–485, 2017.
- [5] G. Mitteramskogler, R. Gmeiner, R. Felzmann et al., "Light curing strategies for lithography-based additive manufacturing of customized ceramics," *Additive Manufacturing*, vol. 1-4, pp. 110–118, 2014.
- [6] H. Li, L. Song, J. Sun, J. Ma, and Z. Shen, "Dental ceramic prostheses by stereolithography-based additive manufacturing: potentials and challenges," *Advances in Applied Ceramics*, vol. 118, no. 1-2, pp. 30–36, 2018.
- [7] Y. Lu, Z. Mei, J. Zhang et al., "Flexural strength and Weibull analysis of Y-TZP fabricated by stereolithographic additive manufacturing and subtractive manufacturing," *Journal of the European Ceramic Society*, vol. 40, no. 3, pp. 826–834, 2020.
- [8] R. B. Osman, A. J. van der Veen, D. Huiberts, D. Wismeijer, and N. Alharbi, "3D-printing zirconia implants; a dream or a reality? An in-vitro study evaluating the dimensional accuracy, surface topography and mechanical properties of printed zirconia implant and discs," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 75, pp. 521–528, 2017.
- [9] R. G. Craig, W. J. O'Brien, and J. M. Powers, *Dental Materials-Properties and Manipulation*, St Louis: CV Mosby, 2000.
- [10] ASTM C1372-2015, *Standard Test Method for Vickers Indentation Hardness of Advanced Ceramics*, American Society of Testing Materials, America, 2015.
- [11] D. Ćorić, M. Majić Renjo, and L. Ćurković, "Vickers indentation fracture toughness of Y-TZP dental ceramics," *International Journal of Refractory Metals and Hard Materials*, vol. 64, pp. 14–19, 2017.
- [12] J. Gong, J. Wu, and Z. Guan, "Analysis of the indentation size effect on the apparent hardness for ceramics," *Materials Letters*, vol. 38, no. 3, pp. 197–201, 1999.
- [13] M. Majic Renjo, L. Curkovic, S. Stefancic, and D. Coric, "Indentation size effect of Y-TZP dental ceramics," *Dental Materials*, vol. 30, no. 12, pp. e371–e376, 2014.
- [14] H. Li and R. C. Bradt, "The microhardness indentation load/size effect in rutile and cassiterite single crystals," *Journal of Materials Science*, vol. 28, no. 4, pp. 917–926, 1993.
- [15] J. Gong, J. Wu, and Z. Guan, "Load dependence of the apparent hardness of silicon nitride in a wide range of loads," *Materials Letters*, vol. 35, no. 1-2, pp. 58–61, 1998.
- [16] J. Gong and Z. Guan, "Load dependence of low-load Knoop hardness in ceramics: a modified PSR model," *Materials Letters*, vol. 47, no. 3, pp. 140–144, 2001.
- [17] G. R. Anstis, P. Chantikul, B. R. Lawn, and D. B. Marshall, "A critical evaluation of indentation techniques for measuring fracture toughness: I, direct crack measurements," *Journal of the American Ceramic Society*, vol. 64, no. 9, pp. 533–538, 1981.
- [18] Y. Zhang and B. R. Lawn, "Evaluating dental zirconia," *Dental Materials*, vol. 35, no. 1, pp. 15–23, 2019.
- [19] U. Scheithauer, E. Schwarzer, H. J. Richter, and T. Moritz, "Thermoplastic 3D printing-an additive manufacturing method for producing dense ceramics," *International Journal of Applied Ceramic Technology*, vol. 12, no. 1, pp. 26–31, 2015.
- [20] B. Stawarczyk, A. Emslander, M. Roos, B. Sener, F. Noack, and C. Keul, "Zirconia ceramics, their contrast ratio and grain size depending on sintering parameters," *Dental Materials Journal*, vol. 33, no. 5, pp. 591–598, 2012.
- [21] ISO 6872-2015, "Dentistry-Dental Ceramics, International Organization for Standardization," Switzerland, 2015.
- [22] L. Wang, R. Dou, M. Bai, Y. Li, D. Hall, and Y. Chen, "Characterisation of microstructure and hardness of perovskite-structured  $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\delta}$  under different sintering conditions," *Journal of the European Ceramic Society*, vol. 36, no. 7, pp. 1659–1667, 2016.
- [23] K. J. Jang, J. H. Kang, J. G. Fisher, and S. W. Park, "Effect of the volume fraction of zirconia suspensions on the microstructure and physical properties of products produced by additive manufacturing," *Dental Materials*, vol. 35, no. 5, pp. e97–e106, 2019.



- [24] E. Özkol, W. Zhang, J. Ebert, and R. Telle, "Potentials of the "direct inkjet printing" method for manufacturing 3Y-TZP based dental restorations," *Journal of the European Ceramic Society*, vol. 32, no. 10, pp. 2193–2201, 2012.
- [25] M. Saâdaoui, F. Khaldoun, J. Adrien, H. Reveron, and J. Chevalier, "X-ray tomography of additive-manufactured zirconia: processing defects - strength relations," *Journal of the European Ceramic Society*, vol. 40, no. 8, pp. 3200–3207, 2020.
- [26] K. Harada, A. Shinya, D. Yokoyama, and A. Shinya, "Effect of loading conditions on the fracture toughness of zirconia," *Journal of Prosthodontic Research*, vol. 57, no. 2, pp. 82–87, 2013.
- [27] R. He, W. Liu, Z. Wu et al., "Fabrication of complex-shaped zirconia ceramic parts via a DLP- stereolithography-based 3D printing method," *Ceramics International*, vol. 44, no. 3, pp. 3412–3416, 2018.
- [28] S. P. Passos, J. A. Nychka, P. Major, B. Linke, and C. Flores-Mir, "In vitro fracture toughness of commercial Y-TZP ceramics: a systematic review," *Journal of Prosthodontics*, vol. 24, no. 1, pp. 1–11, 2015.
- [29] R. Belli, M. Wendler, J. I. Zorzin, and U. Lohbauer, "Practical and theoretical considerations on the fracture toughness testing of dental restorative materials," *Dental Materials*, vol. 34, no. 1, pp. 97–119, 2018.

## Research Article

# Patient Satisfaction with Implant-Supported Monolithic and Partially Veneered Zirconia Restorations

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Received 19 November 2020; Revised 3 January 2021; Accepted 30 January 2021; Published 8 February 2021

Academic Editor: Chang-Yuan Zhang

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The digital workflow and the application of Computer-Aided Manufacturing (CAM) to prosthodontics present the clinician with the possibility of adopting new materials that confer several advantages. Especially in the case of zirconia, these innovations have profoundly changed daily practice. This paper compares the satisfaction and perception of patients who received implant-supported single crowns (SC) and fixed partial dentures (FPD) made from zirconia, either monolithic or partially veneered, after 3 years of follow-up; the success and survival rate of these restorations were also measured. Forty patients, who had been previously treated with implant-supported SC or FPD, either monolithic or partially veneered, and submitted to a yearly maintenance program, were recalled 3 years after their treatment and requested to complete an 8-question questionnaire regarding their perceptions of the treatment. Any mechanical or biological complication that had occurred from the time of delivery was also recorded. Patients that experienced  $\geq 1$  complication were less likely to be prone to repeat the treatment. The 3-year success rate was 92.6% for monolithic restoration and 92.3% for partially veneered restoration, while the survival rate was 100% for both restorations. The 3-year follow-up found that monolithic and partially veneered zirconia restorations are both well-accepted treatment options, and patients preferred the veneered restorations (0.76,  $p < 0.05$ ) from an aesthetic point of view. According to our results, monolithic and veneered zirconia restorations are both reliable treatment options and are both equally accepted by patients.

## 1. Introduction

The rapid evolution of CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing), and the advancements of its application to dentistry have heralded a series of innovations in all branches, especially in implantology and restorative dentistry, where its association with new materials presents the clinician a new treatment possibility that is both economically advantageous and clinically resilient [1–3].

Two of the most commonly used materials in fixed prosthodontics, zirconia ( $\text{ZrO}_2$ ) and lithium disilicate, are commonly utilized in digital workflows; while zirconia can only be used with this technology, several reports agree that pressed lithium disilicate nevertheless produces better clinical performances [4, 5].

The adoption of CAD/CAM in implant dentistry can provide the clinician with abutments, both in zirconia or titanium, that are shaped appropriately to the position of the implant and the soft tissue characteristics.

Among these materials that can be milled with CAD/CAM technology, zirconia, the crystalline dioxide of zirconium, is by far the most adopted; thanks to its mechanical properties and aesthetic capabilities, it has been also termed ceramic steel [6–8].

Zirconia exists in monoclinic, tetragonal, and cubic phases; with the addition of stabilizing oxides such as MgO, CaO, or Y<sub>2</sub>O<sub>3</sub>, first- and second-generation zirconia are frozen in the tetragonal condition, preventing the so-called martensitic transformation [6]; instead, third-generation zirconia is metastable in the cubic phase [9].

First-generation, or conventional, zirconia, developed almost 20 years ago, has a high light refraction index; therefore, it is an extremely opaque material. As a consequence of these compromised aesthetic characteristics, conventional zirconia is used as a substitute for the cast metal core and therefore veneered with glass-ceramic, providing higher translucency and overall better aesthetic [10]. The adhesion between the veneer and the core has improved since the introduction of this material; nevertheless, cohesive fracture, where a thin layer of ceramic remains on the framework, is still a common complication [11].

To prevent this, zirconia can be used in monolithic restorations, where the whole crown is made of zirconia and no veneers are used. Certain requirements must be met before this material can be used in a monolithic fashion: it is critical that the material is sufficiently translucent and aesthetically pleasing; these requirements are especially met with second-generation zirconia (3Y-TZP), where the number and grain size of aluminum oxide are reduced in terms of number and dimension and repositioned in the zirconia framework: this allows for higher transmittance of light, with good stability and high strength, even if lower than the previous generations of zirconia [12].

To achieve the translucency of other glass-ceramics, third-generation zirconia (5Y-TZP) was introduced; contrary to the previous two generations, this zirconia contains up to 53% of the cubic phase: this was achieved by the introduction of a higher percentage (from 4% to 5%) of yttrium. Third-generation zirconia has quite interesting properties: it can be used at extremely low occlusal thickness [13] thanks to its higher flexural strength; therefore, it is more conservative than other conventional restorative materials [14] (such as lithium disilicate or porcelain fused to metal) while at the same time providing the appropriate aesthetics, [15] especially when layered precolored zirconia is used, which offers several aesthetic advantages, and can help manufacture a more natural and aesthetically pleasing crown when compared to monochrome zirconia [16].

The main purpose of this paper was to analyze, via a questionnaire, the satisfaction and perception of patients who received a monolithic or partially veneered implant-supported restoration, either a single crown (SC) or a fixed partial denture (FPD), at 3 years after delivery. Also, the restorations were analyzed at the 3-year follow-up, and the antagonist was inspected to evidence any wear of its occlusal surface. The clinical outcomes after the 3-year follow-up, e.g., the frequency and type of complications, were also recorded.

## 2. Materials and Methods

**2.1. Study Design.** Patients who had undergone monolithic or partially veneered zirconia SCs and FPDs, in the molar to premolar area, on dental implants between January 1, 2017, and June 1, 2017, were screened and invited to participate in the survey.

All procedures took place at two private dental practices in Ascoli Piceno, Italy, and Rome, Italy. All procedures were performed according to the Declaration of Helsinki guidelines on experimentation involving human subjects. Each participant enrolled in the study received adequate explanations on the study design and objectives and provided written informed consent. Due to the retrospective nature of this study, it was granted an exemption in writing by the local ethics committee.

**2.2. Participants.** We included patients that (1) were willing to provide informed consent and participate in the study and (2) had available information on the date the prosthesis was delivered and on the eventual complications. We excluded patients that (1) could not answer to the questionnaire due to neurological or psychological disorders.

**2.3. Clinical Procedures.** The implant position was based on a prosthetic-guided planning developed after performing an exhaustive clinical and radiologic examination; implant fixtures were inserted under local anesthesia following the manufacturer's guidelines (Straumann Implant System, Biomet 3i Implant System).

After a healing period of 3 months, either a conventional impression or a digital impression was taken.

In subjects that followed a conventional workflow, an impression was taken with alginate impression material (Xantalgin, Mitsui Chemical Group, Tokyo, Japan) and stock trays to manufacture a custom impression tray. The final impression was taken using the open tray technique and polyether impression material (Impregum Penta Soft Quick Step MB, 3M ESPE) following the manufacturer's guidelines.

In subjects that followed a digital workflow, a scan-body abutment was screwed to the implant body, and a scan of both arches, as well as of the occlusion, was registered (Trios 3, 3SHAPE). The standard tessellation language (STL) file was then sent to the dental technician.

The restorations were designed as either cement-retained or screw-retained. If feldspathic porcelain was to be added on the buccal side, the zirconia structure was intraorally tried with the buccal cut back applied and then sent back to the dental laboratory to be veneered.

High-translucency (HT) zirconia was utilized, in the form of inCoris TZI (Sirona) and Biodynamic Multilayer 1200/600 Mpa Progressive (Biodynamic). The former is a HT zirconia with flexural strength > 900 MPa, while the latter is a more innovative material that presents higher flexural strength in the cervical region (1200 MPa), where more mechanical strength is needed, and lower flexural strength (600 MPa) in the incisal region, where more translucency is preferred.

Cement-retained prostheses were cemented with a glass-ionomer cement on titanium stock abutments, previously screwed to the implant fixture following the manufacturer's guidelines, carefully removing the excess cement. FPDs (hybrid cement-screw-retained) were bonded extraorally to prefabricated metal substructures (screw-retained abutments). Screw-retained single crowns were bonded to prefabricated titanium base abutments. All the crowns and bridges were bonded using an adhesive luting composite (Multilink Hybrid Abutment, Ivoclar, Schaan, Liechtenstein) and finally polished.

The screw-retained prostheses were seated on the implants and screwed using a manual torque control ratchet (20 N/cm). The screw access holes were packed with polytetrafluoroethylene tape and covered with composite resin. The complete removal of excess cement and seating of the restorations were checked with a radiograph taken immediately after delivery of the restoration.

After the prosthesis delivery, all patients were enrolled in a personalized maintenance care program based on the risk assessment of the patients.

**2.4. Outcomes and Data Collection.** The primary purpose was evaluating if, 3 years after the rehabilitation, patients were satisfied from a functional and aesthetic point of view, and if they were willing to undergo the same procedure in the future, if needed. The secondary purpose was to define clinical outcomes, such as the number and type of complications, and wear of the restoration and of the opposing dentition after a 3-year follow-up.

A restoration was defined as a success if there had not been any kind of complication; a restoration was defined as surviving if it was still in use at the 3-year follow-up [17].

The analyzed factors were the use of axial or tilted implants, the type of edentulism, the presence or absence of parafunctions, and the design of the restoration (either screw-retained or cement-retained and either monolithic or partially stratified).

Furthermore, we examined the correlation between the frequency of mechanical and biological complications and the willingness to undergo a similar procedure.

The following information was obtained from the clinical chart:

- (i) Number and type of implants placed
- (ii) Type of rehabilitation
- (iii) Presence of parafunctions
- (iv) Number and type of complications

Each recruited subject contributed with a single rehabilitation.

At the recall visit, the corresponding restorations and opposing dentition were examined.

Complications were divided into technical and biological. Technical complications were also divided into major and minor complications, as suggested by Lang et al. [18].

Wear of the restoration and/or the opposing dentition were clinically assessed using magnifying loupes.

Biological complications were assessed by performing periodontal probing and recording the probing depth (PD), bleeding on probing (BoP), and presence of suppuration. Marginal bone loss was analyzed using standardized intraoral radiographs at baseline, after prosthesis delivery, and at the 3-year follow-up. Peri-implant mucositis and peri-implantitis were defined following the guidelines by Renvert et al. [19].

An independent investigator provided subjects with a questionnaire, which started with a question asking them to indicate the location of the rehabilitation. Data for the analyses were extracted only from the questionnaire of subjects who had provided the correct answer to the initial question. An operator external to the previous treatment was instructed to collect these questionnaires [20].

The patients were also asked to mark on 100 mm visual analogue scales (VAS) the appropriate answers to the following questions:

- (1) How would you rate the appearance of your teeth immediately after their treatment?
- (2) How would you rate the appearance of those teeth today?
- (3) How would you rate your present capacity to chew?
- (4) How would you rate your present capacity to speak?
- (5) How easy do you find it to clean your teeth and gums?
- (6) What did you think about the financial cost of your treatment at the time of treatment?
- (7) In hindsight, how would you rate the initial financial cost of your dental treatment?
- (8) In hindsight, would you undergo the treatment you had for your mouth and teeth again?

Each patient was asked to fill out the questionnaire themselves to ensure as little bias as possible.

**2.5. Statistical Analysis.** Two separate investigators (P.D., E.R.) extracted the required data from the questionnaire and inserted it into two separate spreadsheets, which were then compared to check for any discrepancies; a single database was then obtained, which included the participants' demographic data, their responses to the questionnaire, and the clinical characteristics previously recorded.

Descriptive statistics were used to illustrate the overall gathered responses as means and standard deviations (SD), while binary outcomes were reported as a prevalence.

The outcomes of interest were the patients' responses to the questionnaire, recorded on a 1–10 VAS scale (continuous variable), and the willingness to undergo the procedure again if needed (binary outcome, yes/no).

Linear (for continuous variables) and logistic (for binary outcomes) regression models were produced depending on

the stated outcomes to test the correlations between the gathered patient responses, demographics, and obtained clinical data to the stated variables of interest. A stepwise regression approach was used for the variables of interest to test their predictive values, and the variables were kept for multivariate modeling if they obtained  $p < 0.05$ .

All analyses were performed in R Studio (Integrated Development for R. RStudio, PBC, Boston) by a separate investigator.

### 3. Results

Table 1 presents the characteristics of the sample, divided according to the design of the rehabilitations.

Among the 71 patients eligible for recruitment, 48 were contacted and agreed to participate in the present evaluation. Among them, eight (16.6%) were excluded because they were unable to remember the location of the procedure. Therefore, 40 patients constituted the sample in the present study.

Twenty-seven patients received monolithic zirconia restorations, while 13 received partially veneered zirconia restorations; 26 patients received a FPD, while the remaining 14 received a SC. 27 patients were treated with a conventional workflow, while 13 with a digital workflow.

The success rate for monolithic restorations was 92.6%, while that for the veneered restorations was 92.3%. Overall, two restorations (5%) had a mechanical complication: one screw-retained monolithic single crown experienced a screw loosening, which was solved by retightening the screw at 35 N/cm, and one 4-unit, cement-retained, veneered FPD, occluding with a fixed partial denture, underwent a chipping of the veneering ceramic, possibly as a consequence of the parafunctional behavior of the subject; as the chipping was minor, this complication was resolved only by polishing the surface.

Three implants (4.2%) experienced biological complications: one implant supporting a FPD had signs of peri-implantitis, while two other cases of FPD had signs of peri-implant mucositis (Figure 1). At the recall appointment, patients with biological complications underwent a motivational session and a session to reexplain oral hygiene instructions followed by a professional nonsurgical therapy together with the use of chlorhexidine mouthwashes and gels.

The survival rate was 100% for both the monolithic restorations and partially veneered restorations, as all implant-supported restorations were still functioning at the 3-year mark, irrespective of the condition of the implants or the restoration.

At the 3-year follow-up, medical loupes and 5x magnification revealed no wear of the restorations and the opposing dentition.

**3.1. Patients' Responses and Correlation to Recorded Outcomes.** Figure 2 presents the responses to the questionnaire. Patients that had a partially veneered restoration believed their restoration to be more aesthetically pleasant both when it was delivered (Q1) ( $0.76, p < 0.05$ ) and as it appeared at the recall appointment (Q2) ( $0.85, p < 0.01$ ) than those who received a monolithic restoration. The other mea-

TABLE 1: Characteristics of the sample.

Characteristic	Monolithic	Partially veneered
<i>Number of patients</i>	27 (67.5%)	13 (32.5%)
<i>Type of rehabilitation</i>		
Fixed partial denture	17	9
Single crown	10	4
<i>Type of prosthesis</i>		
Cement-retained	6	5
Screw-retained	21	8
<i>Parafunction</i>		
Yes	5	5
No	20	8
<i>Number of implants</i>		
1	10	4
2	14	7
3	3	2
<i>Number of mechanical complications</i>	1 (3.7%)	1 (7.7%)
<i>Number of biological complications</i>	2 (7.4%)	1 (7.7%)
<i>Would repeat the treatment?</i>		
Yes	26	11
No	1	2

sured outcomes had no effect. Patients who had  $>2$  implants ( $-0.9, p < 0.05$ ) or who had tilted implants ( $-0.58, p < 0.05$ ) reported more difficulties in maintaining proper oral hygiene (Q5). Moreover, patients who experienced biological complications were more likely to report higher difficulties in maintaining proper oral hygiene (Kruskal-Wallis,  $p < 0.01$ ).

Patients that received partially veneered restorations reported being much less happy about the price of their restoration (Q6) when the prosthesis was delivered ( $-0.94, p < 0.001$ ), but this difference was no longer definable at the last recall appointment, as patients who received screw-retained restorations ( $1.76, p < 0.001$ ) were more likely to report a high score to Q7, while patients who experienced complications ( $-2.5, p < 0.001$ ) or patients with a single implant restoration ( $-1.14, p < 0.05$ ) were less satisfied with the payment they had made years before. None of the recorded factors played a role in determining the perceived capability to speak (Q3) or chew (Q4).

**3.2. Willingness to Undergo the Same Procedure.** Overall, the procedure was fairly acceptable to patients, as only three were not willing to undergo the same procedure (8%). Patients who had a complication, either biological or mechanical, were much less likely to be willing to repeat the same procedure (odds ratio [OR] 22.72,  $p < 0.05$ ); no other correlations were found with the recorded outcomes.

### 4. Discussion

The main purpose of the study was to focus on patient perceptions of implant-supported rehabilitations performed





FIGURE 1: Peri-implant mucositis of the 1.5 and peri-implantitis of the 1.7.

using monolithic or partially veneered zirconia. CAD/CAM procedures and digital workflow are now common in daily clinical practice because of their excellent results in terms of use and quality obtained [21].

The secondary purpose was to assess the success and survival rate of monolithic or partially veneered zirconia restorations after 3 years. In the present study, we included patients treated in two clinical settings by two experienced prosthodontists following standardized clinical protocols. All parameters investigating the patient's perceptions were assessed using a questionnaire administered by the same investigator to achieve objective results. Furthermore, to include only patients that had actual recollection of the procedure, we excluded patients that did not remember the side of the restoration.

The literature has an increasing number of clinical long-term studies of implant-supported restorations, with relevant information on the clinical outcomes. However, patient-evaluated dentistry is increasingly being recognized as a necessary consideration to determine the overall prosthodontic success. Information on patient satisfaction following the clinical protocols described in the present study are still lacking in the literature [20].

The results of our investigation confirm that, after a 3-year follow-up, monolithic and partially veneered zirconia restorations are both well-accepted treatment options. The results also show that partially veneered restorations are associated with a statistically significant higher aesthetic score, outlining the fact that patients find veneered restorations more aesthetically pleasant than monolithic restorations, but in our sample, no monolithic restorations experienced any fracture, while one veneered crown experienced chipping of the veneering material.

However, favourable aesthetic results were achieved for both groups. On the other hand, patients perceived no differ-

ences from a functional point of view, considering the reported ability to chew and speak, similar to that reported in the literature [22].

The analysis of the questionnaire indicated that patients who had >2 implants or who had tilted implants reported more difficulties in maintaining proper oral hygiene. Furthermore, patients who developed biological complications reported having had difficulties in maintaining proper oral hygiene. This finding is in line with the results of Pons et al. [23], who observed that poor access to proximal hygiene presented increased risk of developing peri-implant disease, in particular peri-implant mucositis. Furthermore, the same study also reported that the presence of peri-implant disease was related to self-reported assessment of oral hygiene measures and to patient perception of gingival/mucosal bleeding when performing oral hygiene.

These results show the ability of the patients, who were carefully selected and enrolled in a maintenance program, to perceive when proper oral hygiene was performed. Finally, the significant association observed between the occurrence of complications and the willingness to undergo the same procedure or the cost perceived by the patients should also be considered with care. Gargallo-Albiol et al. reported similar results on patients' perception of dental implant removal following complications, reporting a certain reluctance in patients to undergo future implant placement in the same clinic or with the same professional [24].

Our report also states that monolithic zirconia crowns have good clinical performances, given the low complication rate reported. This is the major advantage of monolithic zirconia crowns over conventional veneered restorations: for the latter, even when zirconia-based, chipping of the veneering material is the main and most frequent technical complication [25], whereas Y-TZP is the toughest ceramic material available on the market, notably reducing the rate of complications for the former [26]. In the present paper, monolithic restorations had a higher success rate than veneered restorations, similarly to that reported by other authors [27, 28].

Although HT zirconia is much more resistant than porcelain, vestibular feldspathic veneers are still preferred in cases where aesthetic is paramount, such as the restoration of a central incisor, or when the chromatic characteristics of the adjacent teeth make it difficult for the dental technician to properly give the crown the required color. According to our findings, monolithic zirconia was aesthetically satisfactory and accepted by the patients, even after 3 years.

Some papers have reported the possibility that the techniques used to superficially color zirconia may not be stable over time [29, 30], as this superficial layer could potentially wear off as a consequence of the natural abrasions that occur during use. We did not report this phenomenon in the present study, as the monolithic zirconia crowns were all integrated in the oral cavity and the patients reported no change in their color, similarly to what other papers have found [31, 32].

Moreover, eliminating the necessity of a veneer enables the restoration to be thinner; the preparation on natural teeth can be less extensive as a monolithic zirconia crown with a thickness of 0.7 mm on the occlusal surface has sufficient

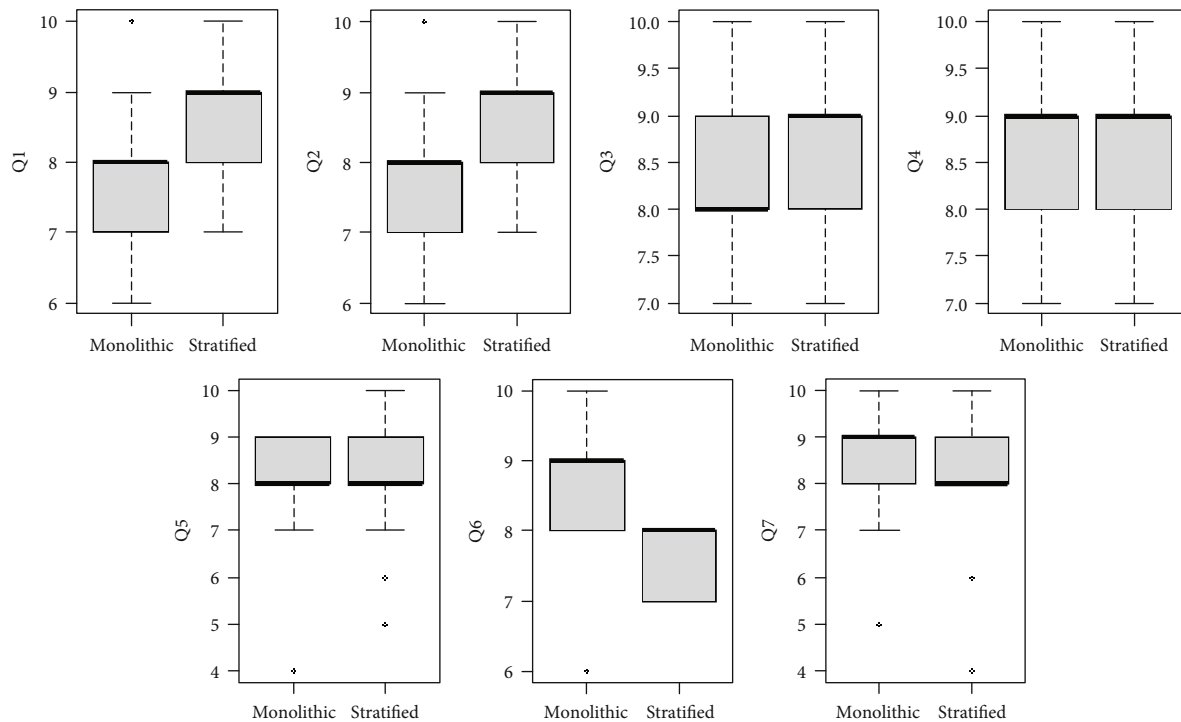


FIGURE 2: Box plots of the recorded questionnaire responses.

fracture resistance to be used as an implant-supported restoration [33].

One previously reported flaw of monolithic zirconia crowns is that, given the superior hardness of the material ( $H_v \approx 1200$  GPa; double that of porcelain [34]), zirconia could be more abrasive to enamel than other restorative materials, at least on paper, especially if not polished properly [35]; recent systematic reviews have concluded though that monolithic zirconia is not more abrasive than other, commonly used, restorative materials, at least in in vitro studies [36, 37].

From our clinical observations, wear of enamel on the antagonist teeth of monolithic zirconia crowns was no different from that observed on the adjacent teeth.

Implant-supported SCs are the standard of care for replacing a missing single tooth, and implant-supported monolithic zirconia crowns have a high survival rate, comparable to classical PFM (porcelain-fused-to-metal) crowns [38]. They can be both cement-retained or screw-retained, and while both are clinically acceptable, screw-retained crowns have some clear advantages and are therefore nowadays preferred, as extrusion of cement in the peri-implant tissues during cementation can lead to biological complications [39]. Also, when monolithic zirconia crowns are fabricated to be hybrid cement-screw-retained, they are cemented extra-orally on titanium bases; the abutment is completely surrounded by zirconia, thereby having an aesthetic material underneath the soft tissues, avoiding the greyish aspect that sometimes can develop, especially in extremely thin biotypes, with restorations cemented on titanium abutments [40].

The main limitation of this study is its retrospective nature, as patients that did not agree to the recall visit might

have had a higher rate of complications, which barred them from attending the appointment.

Moreover, our sample is quite heterogenous, as we included both SCs and FPDs on two or three implants, axial and tilted. Finally, our considerations on color and wear of the delivered prostheses are only based on our clinical observations, as no volumetric or colorimetric approach was adopted.

Long-term randomized controlled studies should be carried out to determine the patient perception of these two prosthetic approaches and their clinical reliability in standardized clinical conditions.

## 5. Conclusions

Given the high success rate found in the present study, monolithic and partially veneered zirconia restorations can both be defined as reliable treatment options for implant-supported SCs and FPDs. However, a statistically significant difference was found, outlining the fact that veneered restorations are more esthetically pleasant than monolithic restorations. Therefore, especially in the visible area, adding a partial veneer can improve the aesthetics while at the same time maintaining an acceptable rate of complications.

## Data Availability

The data of the study can be asked to the corresponding author.



## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

## References

- [1] T. Joda, J. Katsoulis, and U. Brägger, "Clinical fitting and adjustment time for implant-supported crowns comparing digital and conventional workflows," *Clinical Implant Dentistry and Related Research*, vol. 18, no. 5, pp. 946–954, 2016.
- [2] T. Joda and U. Brägger, "Digital vs. conventional implant prosthetic workflows: a cost/time analysis," *Clinical Oral Implants Research*, vol. 26, no. 12, pp. 1430–1435, 2015.
- [3] P. De Angelis, P. F. Manicone, S. De Angelis et al., "Patient and operator centered outcomes in implant dentistry: comparison between fully digital and conventional workflow for single crown and three-unit fixed-bridge," *Materials (Basel)*, vol. 13, no. 12, p. 2781, 2020.
- [4] P. Gerogianni, W. Lien, D. Bompolaki et al., "Fracture resistance of pressed and milled lithium disilicate anterior complete coverage restorations following endodontic access preparation," *Journal of Prosthodontics*, vol. 28, no. 2, pp. 163–170, 2019.
- [5] F. Homsy, M. Bottin, M. Özcan, and Z. Majzoub, "Fit accuracy of pressed and milled lithium disilicate inlays fabricated from conventional impressions or a laboratory-based digital workflow," *The European Journal of Prosthodontics and Restorative Dentistry*, vol. 27, no. 1, pp. 18–25, 2019.
- [6] R. C. Garvie, R. H. Hannink, and R. T. Pascoe, "Ceramic steel?," *Nature*, vol. 258, no. 5537, pp. 703–704, 1975.
- [7] P. F. Manicone, P. Rossi Iommetti, and L. Raffaelli, "An overview of zirconia ceramics: basic properties and clinical applications," *Journal of Dentistry*, vol. 35, no. 11, pp. 819–826, 2007.
- [8] P. F. Manicone, P. R. Iommetti, L. Raffaelli et al., "Biological considerations on the use of zirconia for dental devices," *International Journal of Immunopathology and Pharmacology*, vol. 20, Supplement 1, pp. 9–12, 2017.
- [9] "Three generations of zirconia: from veneered to monolithic. Part I," *Quintessence International*, vol. 48, no. 5, pp. 369–380, 2017.
- [10] I. Sailer, M. Strasding, N. A. Valente, M. Zwahlen, S. Liu, and B. E. Pjetursson, "A systematic review of the survival and complication rates of zirconia-ceramic and metal-ceramic multiple-unit fixed dental prostheses," *Clinical Oral Implants Research*, vol. 29, Supplement 16, pp. 184–198, 2018.
- [11] F. Cantner, C. Cacaci, T. Mücke, P. Randelzhofer, J. Hajtő, and F. Beuer, "Clinical performance of tooth- or implant-supported veneered zirconia single crowns: 42-month results," *Clinical Oral Investigations*, vol. 23, no. 12, pp. 4301–4309, 2019.
- [12] V. Koenig, C. Wulfman, S. Bekaert et al., "Clinical behavior of second-generation zirconia monolithic posterior restorations: Two-year results of a prospective study with \_Ex vivo\_ analyses including patients with clinical signs of bruxism," *Journal of Dentistry*, vol. 91, article 103229, 2019.
- [13] G. K. R. Pereira, L. F. Guilardi, K. S. Dapieve, C. J. Kleverlaan, M. P. Rippe, and L. F. Valandro, "Mechanical reliability, fatigue strength and survival analysis of new polycrystalline translucent zirconia ceramics for monolithic restorations," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 85, pp. 57–65, 2018.
- [14] N. Nordahl, P. Vult von Steyern, and C. Larsson, "Fracture strength of ceramic monolithic crown systems of different thickness," *Journal of Oral Science*, vol. 57, no. 3, pp. 255–261, 2015.
- [15] F. Tabatabaian, "Color aspect of monolithic zirconia restorations: a review of the literature," *Journal of Prosthodontics*, vol. 28, no. 3, pp. 276–287, 2019.
- [16] K. Ueda, J.-F. Güth, K. Erdelt, M. Stimmelmayer, H. Kappert, and F. Beuer, "Light transmittance by a multi-coloured zirconia material," *Dental Materials Journal*, vol. 34, no. 3, pp. 310–314, 2015.
- [17] N. P. Lang, L. Pun, K. Y. Lau, K. Y. Li, and M. C. M. Wong, "A systematic review on survival and success rates of implants placed immediately into fresh extraction sockets after at least 1 year," *Clinical Oral Implants Research*, vol. 23, Supplement 5, pp. 39–66, 2012.
- [18] N. P. Lang, N. U. Zitzmann, and Working Group 3 of the VIII European Workshop on Periodontology, "Clinical research in implant dentistry: evaluation of implant-supported restorations, aesthetic and patient-reported outcomes," *Journal of Clinical Periodontology*, vol. 39, Supplement 12, pp. 133–138, 2012.
- [19] S. Renvert, G. R. Persson, F. Q. Pirih, and P. M. Camargo, "Peri-implant health, peri-implant mucositis, and peri-implantitis: case definitions and diagnostic considerations," *Journal of Periodontology*, vol. 89, Supplement 1, pp. S304–S312, 2018.
- [20] D. Layton and T. Walton, "Patient-evaluated dentistry: development and validation of a patient satisfaction questionnaire for fixed prosthodontic treatment," *The International Journal of Prosthodontics*, vol. 24, p. 10, 2011.
- [21] C. Monaco, M. Caldari, R. Scotti, and AIOP (Italian Academy of Prosthetic Dentistry) Clinical Research Group, "Clinical evaluation of zirconia-based restorations on implants: a retrospective cohort study from the AIOP clinical research group," *The International Journal of Prosthodontics*, vol. 28, pp. 239–242, 2016.
- [22] F. Nejatidanesh, H. Moradpoor, and O. Savabi, "Clinical outcomes of zirconia-based implant- and tooth-supported single crowns," *Clinical Oral Investigations*, vol. 20, no. 1, pp. 169–178, 2016.
- [23] R. Pons, J. Nart, C. Valles, G. E. Salvi, and A. Monje, "Self-administered proximal implant-supported hygiene measures and the association to peri-implant conditions," *Journal of Periodontology*, 2020.
- [24] J. Gargallo-Albiol, L. Tavelli, S. Barootchi, A. Monje, and H.-L. Wang, "Clinical sequelae and patients' perception of dental implant removal: a cross-sectional study," *Journal of Periodontology*, 2020.
- [25] A. J. Raigrodski, M. B. Hillstead, G. K. Meng, and K.-H. Chung, "Survival and complications of zirconia-based fixed dental prostheses: a systematic review," *The Journal of Prosthetic Dentistry*, vol. 107, no. 3, pp. 170–177, 2012.
- [26] P. De Angelis, P. C. Passarelli, G. Gasparini, R. Boniello, G. D'Amato, and S. De Angelis, "Monolithic CAD-CAM lithium disilicate versus monolithic CAD-CAM zirconia for single implant-supported posterior crowns using a digital workflow: a 3-year cross-sectional retrospective study," *The Journal of Prosthetic Dentistry*, vol. 123, no. 2, pp. 252–256, 2020.
- [27] P. Rammelsberg, A. Meyer, J. Lorenzo-Bermejo, S. Kappel, and A. Zenthöfer, "Long-term chipping and failure rates of implant-supported and combined tooth-implant-supported

- metal-ceramic and ceramic fixed dental prostheses: a cohort study," *The Journal of Prosthetic Dentistry*, no. 20, pp. 30391–30397, 2020.
- [28] P. Rammelsberg, J. Lorenzo Bermejo, S. Kappel, A. Meyer, and A. Zenthöfer, "Long-term performance of implant-supported metal-ceramic and all-ceramic single crowns," *Journal of Prosthodontic Research*, vol. 64, no. 3, pp. 332–339, 2020.
- [29] R. Derafshi, H. Khorshidi, M. Kalantari, and I. Ghaffarlou, "Effect of mouthrinses on color stability of monolithic zirconia and feldspathic ceramic: an in vitro study," *BMC Oral Health*, vol. 17, no. 1, p. 129, 2017.
- [30] M. G. Subaşı, G. Alp, W. M. Johnston, and B. Yilmaz, "Effects of fabrication and shading technique on the color and translucency of new-generation translucent zirconia after coffee thermocycling," *The Journal of Prosthetic Dentistry*, vol. 120, no. 4, pp. 603–608, 2018.
- [31] A. Papageorgiou-Kyran, M. Kokoti, E. Kontonasaki, and P. Koidis, "Evaluation of color stability of preshaded and liquid-shaded monolithic zirconia," *The Journal of Prosthetic Dentistry*, vol. 119, no. 3, pp. 467–472, 2018.
- [32] G. Alp, M. G. Subaşı, R. R. Seghi, W. M. Johnston, and B. Yilmaz, "Effect of shading technique and thickness on color stability and translucency of new generation translucent zirconia," *Journal of Dentistry*, vol. 73, pp. 19–23, 2018.
- [33] T.-H. Lan, P.-H. Liu, M. M. C. Chou, and H.-E. Lee, "Fracture resistance of monolithic zirconia crowns with different occlusal thicknesses in implant prostheses," *The Journal of Prosthetic Dentistry*, vol. 115, no. 1, pp. 76–83, 2016.
- [34] T. Miyazaki, T. Nakamura, H. Matsumura, S. Ban, and T. Kobayashi, "Current status of zirconia restoration," *Journal of Prosthodontic Research*, vol. 57, no. 4, pp. 236–261, 2013.
- [35] R. Pfefferle, N. Lümke, F. Wiedenmann, and B. Stawarczyk, "Different polishing methods for zirconia: impact on surface, optical, and mechanical properties," *Clinical Oral Investigations*, vol. 24, no. 1, pp. 395–403, 2020.
- [36] M. Gou, H. Chen, J. Kang, and H. Wang, "Antagonist enamel wear of tooth-supported monolithic zirconia posterior crowns in vivo: a systematic review," *The Journal of Prosthetic Dentistry*, vol. 121, no. 4, pp. 598–603, 2019.
- [37] M. F. Solá-Ruiz, A. Baima-Moscardó, E. Selva-Otaola, et al., "Wear in antagonist teeth produced by monolithic zirconia crowns: a systematic review and meta-analysis," *Journal of Clinical Medicine*, vol. 9, no. 4, p. 997, 2020.
- [38] P. Moilanen, J. Hjerpe, L. V. J. Lassila, and T. O. Närhi, "Fracture strength and precision of fit of implant-retained monolithic zirconia crowns," *Journal of Oral Implantology*, vol. 44, no. 5, pp. 330–334, 2018.
- [39] N. Staubli, C. Walter, J. C. Schmidt, R. Weiger, and N. U. Zitzmann, "Excess cement and the risk of peri-implant disease - a systematic review," *Clinical Oral Implants Research*, vol. 28, no. 10, pp. 1278–1290, 2017.
- [40] M. Ferrari, M. Carrabba, A. Vichi, C. Goracci, and M. Cagidiaco, "Influence of abutment color and mucosal thickness on soft tissue color," *The International Journal of Oral & Maxillofacial Implants*, vol. 32, no. 2, pp. 393–399, 2017.

## Review Article

# Effects of Aging on the Color and Translucency of Monolithic Translucent Y-TZP Ceramics: A Systematic Review and Meta-Analysis of *In Vitro* Studies

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Received 14 September 2020; Revised 8 December 2020; Accepted 11 January 2021; Published 27 January 2021

Academic Editor: Fernanda Faot

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**Background.** Monolithic restorations made of translucent yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) have become popular over the past few decades. However, whether aging affects the color and translucency of monolithic translucent Y-TZP is unclear. **Objective.** The aim of this systematic review and meta-analysis of *in vitro* studies was to evaluate the effects of aging on the color and translucency of monolithic translucent Y-TZP ceramics. **Materials and Methods.** This systematic review/meta-analysis was reported according to the PRISMA statement and registered in the OSF registries (<https://osf.io/5qjmu>). Four databases including Medline via the PubMed, Embase, and Web of Science databases and the Cochrane Library were searched using no publication year and language limits. The last search was executed on November 20, 2020. *In vitro* studies comparing the translucency and/or color of monolithic translucent Y-TZP ceramics before and after simulated aging were selected. Meta-analyses were performed using Review Manager software (version 5.3, Cochrane Collaboration, Oxford, UK) with random-effects models at a significance level of 0.05. A risk-of-bias assessment was also performed for the included studies. **Results.** Of the 188 potentially relevant studies, 13 were included in the systematic review. The hydrothermal aging duration ranged from 1 to 100 h at relatively similar temperatures (~134°C). In the general meta-analyses, the aged Y-TZP ceramics exhibited similar translucency parameter (TP), L\*, and b\* values compared with the nonaged controls ( $P = .73$ ,  $P = .49$ , and  $P = .62$ , respectively). Moreover, there was a significant difference between the aged and nonaged Y-TZP ceramics in the a\* value ( $P = .03$ ; MD = -0.26; 95% CI = -0.51 to -0.02), favoring the nonaged Y-TZP ceramics. The subgroup analyses showed that the duration of aging contributed to changes in the translucency and color of the Y-TZP ceramics. **Conclusions.** The optical properties of monolithic translucent Y-TZP ceramics were stable after hydrothermal aging at 134°C and 0.2 MPa for ≤20 h. Moreover, clinically unacceptable changes in the translucency and color of monolithic translucent Y-TZP ceramics were found after hydrothermal aging for >20 h.

## 1. Introduction

The popularity of dental zirconia has increased in recent decades because of its excellent mechanical characteristics, biocompatibility, and acceptable esthetic properties [1, 2]. A questionnaire-based survey regarding the selection of dental ceramic materials reported that dental zirconia was one of the top choices for both anterior (layered) and posterior (monolithic) restorations [3].

At ambient pressure, zirconia can exhibit 3 allotropic crystal phase structures: a monoclinic phase (*m*) from room temperature to 1170°C, a tetragonal phase (*t*) from 1170°C to 2370°C, and a cubic phase (*c*) above 2370°C to its melting point at 2715°C and boiling point of 4300°C [4, 5]. To stabilize the *t* and *c* phases of zirconia at room temperature, the addition of different amount of stabilizing oxides, such as yttria (Y<sub>2</sub>O<sub>3</sub>), to pure zirconia crystals is essential and well studied [2, 4, 6]. In particular, *t* phase zirconia is useful in

dentistry because of its strength [2, 6]. Therefore, yttria-stabilized zirconia polycrystal (Y-TZP) has been widely used as a framework for fixed dental prostheses (FDPs) and monolithic restorations [7]. To date, there are three generations of Y-TZP ceramics (1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> generations) in dentistry [2]. First-generation Y-TZP ceramics are 3 mol% (5.2 wt%) Y-TZP (3Y-TZP) containing 0.25 wt% alumina, which are highly opaque. Second-generation Y-TZP ceramics are refined by reducing the concentration of alumina (<0.05 wt%) and sintering at a higher temperature (~1450°C) of 3Y-TZP [2]. To further reduce opacity, 3<sup>rd</sup> generation Y-TZP ceramics are refined by increasing the yttria content to 4 and 5 mol% (4Y-TZP and 5Y-TZP) to stabilize the *c* phase content (>25%) [2]. Both 2<sup>nd</sup> and 3<sup>rd</sup> generations of Y-TZP ceramics are considered translucent and are indicated for posterior and/or anterior monolithic crowns and FDPs [2, 8].

Although *c* phase zirconia does not undergo stress-induced transformation [8], the 2<sup>nd</sup> and 3<sup>rd</sup> generations Y-TZP still have *t* phase so that *t*-to-*m* phase transformation will eventually be activated and accelerated when the Y-TZP ceramic is subjected to a humid environment with constant temperature changes, which is usually referred to as aging or low-temperature degradation (LTD) [9–13]. Evidence of aging has been observed in zirconia used in hip implants [14]. In fact, the mechanism of aging has been described using different theories and speculations [15, 16]. For example, water vapor has been proposed to attack the Zr–O bond and be incorporated into zirconia grains by filling oxygen vacancies; then, aging proceeds into the bulk material and jeopardizes the molecular and mechanical properties of Y-TZP ceramics [17, 18]. On the other hand, Lange et al. [19] proposed that water reacts with Y<sub>2</sub>O<sub>3</sub> to form clusters rich in Y(OH)<sub>3</sub>, which leads to the depletion of the stabilizer in the surrounding zirconia grains and induces aging. This mechanism has also been supported by a recent study [20].

Despite the fact that various aging mechanisms have been proposed, the effects of aging on Y-TZP ceramics are still being studied and reported in the literature [13, 21–23]. The simulated aging of Y-TZP ceramics has commonly been performed by steam autoclave at 120°C to 140°C [16, 24–27]. A recent systematic review concluded that hydrothermal aging promoted LTD, as shown by the *t*-to-*m* phase transformation, and it negatively influenced the flexural strength of Y-TZP ceramics [18]. Moreover, the influences of aging on the surface roughness, surface microhardness, and fracture toughness of Y-TZP ceramics have been previously reported [9, 28–33].

Apart from mechanical properties, optical properties, including color and translucency, are critical for the long-term success of ceramic restorations, especially monolithic restorations [27, 34–36]. However, very limited information concerning the effects of aging on the optical properties of monolithic translucent Y-TZP ceramics (2<sup>nd</sup> and 3<sup>rd</sup> generations) is available. Han et al. [6] reported that autoclaving Y-TZP did not change its color, whereas other treatments such as ultraviolet and gamma irradiation changed the color of Y-TZP. Rafael et al. [37] reported significant differences in the lightness, chroma, and hue of Y-TZP ceramics in all groups after aging. In contrast, other studies have reported

that Y-TZP ceramics can be considered color stable after a stimulated aging process [38, 39]. In addition to the color, efforts have also been made to investigate the effects of aging on the translucency of monolithic translucent Y-TZP ceramics. Current studies in the literature have shown that the translucency of Y-TZP ceramics is reduced [25, 40] or remains unchanged [41] after aging.

Theoretically, Y-TZP ceramic aging may lead to increased surface roughness and pigment breakdown, jeopardizing the esthetic outcome and stability of ceramic restorations [25]. The effects of aging on the color and translucency of monolithic zirconia were reviewed by Papageorgiou-Kyrana et al. [42]. However, no systematic review or meta-analysis has been performed in this field. Therefore, this systematic review and meta-analysis aimed to evaluate the effects of aging on the translucency and color of monolithic translucent Y-TZP ceramics.

## 2. Material and Methods

This systematic review and meta-analysis was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [43] and registered in the OSF registries (<https://osf.io/5qjmu>). A systematic electronic literature search was conducted in Medline via PubMed, Embase, Web of Science (ISI—Web of Knowledge), and Cochrane Library with no publication year and language limits. The search terms and their combinations used in the literature search are listed in Supplemental Table 1. The last search was executed on November 20, 2020. The PICO questions were defined as follows: P: population—monolithic translucent Y-TZP ceramics; I: intervention—Y-TZP ceramics subjected to aging; C: control—Y-TZP ceramics not subjected to aging; O: outcome—an evaluation of color and translucency changes of Y-TZP ceramics; and S: study designs—in vitro studies. The primary evaluated outcome was the translucency of monolithic translucent zirconia, and the secondary evaluated outcome was the color of monolithic translucent zirconia.

Articles that met the following inclusion criteria were included: (1) studies that evaluated the effect of aging on the translucency and/or color of monolithic translucent Y-TZP ceramics and (2) studies that used translucency and/or color measurements according to ISO/TR 28642:2016 [44]. Articles meeting one or more of the following criteria were excluded: (1) study materials other than monolithic translucent Y-TZP ceramics; (2) reviews, protocols, clinical guidelines, and editorial letters; and (3) studies not using hydrothermal aging [33]. Two reviewers (C.Z. and A.C.) independently performed the literature searches and the study selection. Any disagreements were resolved by discussion or by consultation with another reviewer (H.Y.) [33]. The reference lists of all the selected articles were manually reviewed, and the full texts of potentially related studies were examined [45]. Lastly, manual searches were conducted in the following principal periodicals specific to the area of study: Journal of Prosthetic Dentistry, Journal of Dental Research, Journal of Dentistry, Operative Dentistry, Clinical Oral Investigations, Journal of Oral Rehabilitation,



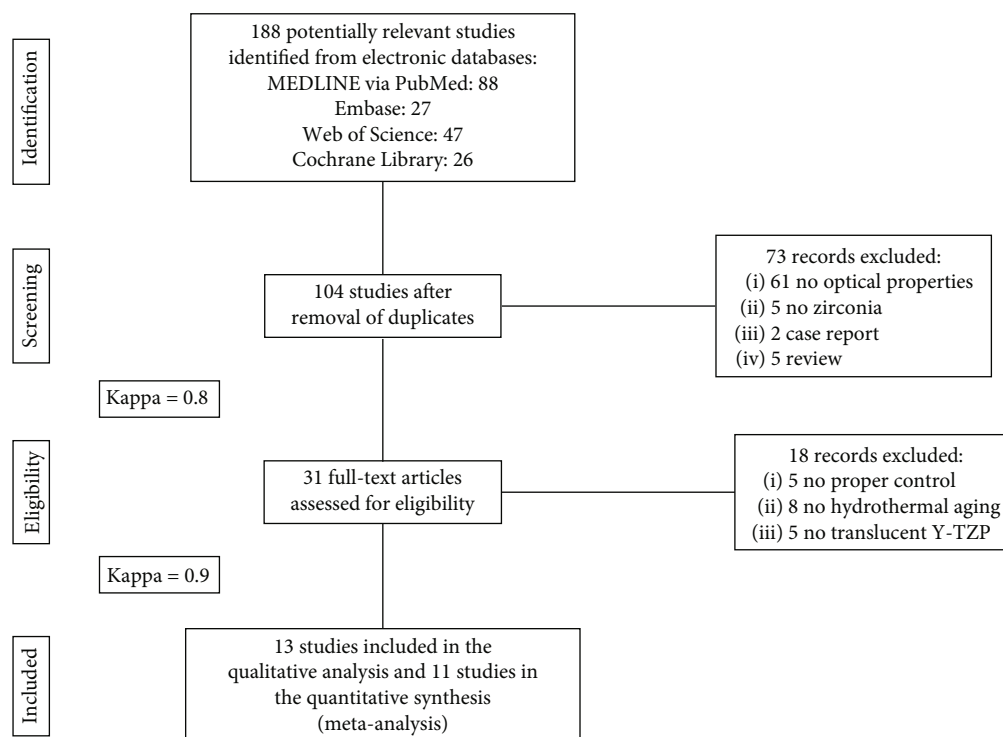


FIGURE 1: Flow diagram of study selection according to the PRISMA statement. PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

International Journal of Prosthodontics, Journal of Prosthodontic Research, Dental Materials Journal, and Journal of Prosthodontics.

A protocol for data extraction was defined and evaluated by 2 reviewers (C.Z. and A.C.) [33]. The following data were extracted from the included studies: demographic information (e.g., authors, publication year, and publication journal and title), the materials tested, the aging protocol, the mean and standard deviation of translucency and/or color, the sample size, and the evaluation methods.

The risk-of-bias assessment was based on a protocol adapted from previous systematic reviews [46, 47]. Briefly, the following parameters were used for the quality assessment: clearly specified aging protocol, sample size calculation, specimen randomization, adequate statistical analysis, ceramic sintering followed the manufacturers' instructions, and tests executed by a single-blinded operator [33]. If a parameter is reported, the study received a "Y"; if the information was missing, the study received an "N." Studies that included 1 or 2 "Y" items were classified as having a high risk of bias, 3 or 4 "Y" items as a medium risk of bias, and 5 to 6 "Y" items as a low risk of bias [33].

For the meta-analysis, studies that did not present data on the translucency parameter (TP) and/or Commission Internationale de L'Eclairage (CIE)  $L^*$ ,  $a^*$ , and  $b^*$  values were excluded. Studies containing the color difference, contrast ratio, and percentage of total transmittance of light were not considered because of insufficient data. For studies that evaluated more than 1 type of ceramic material or 1 aging duration, all the relevant experimental (aged) groups were combined into a single group, and all the relevant control

groups were combined into a single control group according to the Cochrane Statistical Guidelines [48]. All analyses were conducted using Review Manager software (version 5.3; Cochrane Collaboration, Oxford, UK) by employing a random-effects model at a significance level of 0.05. The mean difference (MD) and 95% confidence interval (CI) were calculated for the included studies. Subgroup analyses were performed to explore the potential causes of heterogeneity, including the type of monolithic translucent Y-TZP material (3Y-TZP vs. 5Y-TZP) and the steam autoclave duration ( $\leq 20$  h vs.  $> 20$  h). For the studies included in the subgroup analyses, all the relevant groups were combined into a single subgroup (e.g., 3Y-TZP or 5Y-TZP for the material type) within a given study [48].

### 3. Results

Thirteen studies were included in the systematic review, and 11 studies were included in the meta-analysis (Figure 1). The characteristics of the included studies are presented in Table 1. The majority of the included studies (9 studies) presented a medium risk of bias, while 2 studies presented a high risk of bias and 2 presented a low risk of bias (Table 2).

The included articles were all in English and were published between 2014 and 2020. Of the 13 studies included in the systematic review, 1 study performed color measurements [37], 8 studies performed translucency evaluations [13, 39–41, 49–52], and 4 studies performed both types of investigations [22, 25, 53, 54]. All included studies were laboratory studies measuring the color and/or translucency with a spectrophotometer. All studies included in the meta-

TABLE 1: Characteristics of included studies.

Author	Publication year	Generation of Y-TZP tested	Material tested	Aging protocol	Color measurements	Translucency measurements
Fathy et al.	2015	2 <sup>nd</sup> generation	3Y-TZP: Prettau (Zirkonzahn GmbH)	134°C and 0.2 MPa for 15 h	—	TP
Nakamura et al.	2016	2 <sup>nd</sup> generation	3Y-TZP: Incoris TZi (Dentsply Sirona)	134°C and 0.2 MPa for 5, 10, 20, and 40 h	—	TP and CR
Alghazzawi TF	2017	2 <sup>nd</sup> and 3 <sup>rd</sup> generations	3Y-TZP: Zenostar T (Ivoclar Vivadent), Zirlux (Henry Schein), Katana HT (Kuraray Noritake Dental), Bruxzir (Glidewell Laboratories), DD-BioZX [2] (Dental Direkt GmbH), NexxZr (Sagemax Bioceramics)	134°C and 0.2 MPa for 20, 40, 60, 80, and 100 h	CIE L*a*b* coordinates and color difference ( $\Delta E$ )	TP and CR
			5Y-TZP: DD-cubeX <sup>2</sup> (Dental Direkt GmbH)			Percentage of total transmittance of light (Tt%)
Putra et al.	2017	2 <sup>nd</sup> and 3 <sup>rd</sup> generations	3Y-TZP: Lava Plus (3M ESPE) 5Y-TZP: Bruxzir Anterior (Glidewell Laboratories), Katana UT (Kuraray Noritake Dental)	134°C and 0.2 MPa for 5, 50, and 100 h	—	TP
Rafeal et al.	2018	2 <sup>nd</sup> generation	3Y-TZP: Prettau (Zirkonzahn GmbH)	134°C and 0.3 MPa for 1 h	Color differences ( $\Delta E_{00}$ )	—
Kim and Kim	2019	2 <sup>nd</sup> generation	3Y-TZP: Katana ML (Kuraray Noritake Dental)	134°C and 0.2 MPa for 1, 3, 5, and 10 h	CIE L*a*b* coordinates and color differences ( $\Delta E_{00}$ )	TP
Walczak et al.	2019	2 <sup>nd</sup> generation	3Y-TZP: Cercon ht (Degudent GmbH), Bruxzir (Glidewell Laboratories), Zenostar T (Ivoclar Vivadent), Lava Plus (3M ESPE)	134°C and 0.2 MPa for 5 h	—	TP and CR
Kou et al.	2019	3 <sup>rd</sup> generation	5Y-TZP: DD-cubeX <sup>2</sup> (Dental Direkt GmbH), Bruxzir Anterior (Glidewell Laboratories)	134°C and 0.2 MPa for 10 h	—	Visible transmittance
Shen et al.	2020	2 <sup>nd</sup> and 3 <sup>rd</sup> generations	3Y-TZP: Lava Plus (3M ESPE) 5Y-TZP: Katana UTML (Kuraray Noritake Dental)	134°C and 0.2 MPa for 20 h	—	TP
Benalcazar Jalkh et al.	2020	2 <sup>nd</sup> generation	3Y-TZP: Zpex (Tosoh)	134°C and 0.2 MPa for 20 h	—	TP and CR
de Araújo-Júnior et al.	2020	2 <sup>nd</sup> generation	3Y-TZP: Zirconn translucent (Vipi)	134°C and 0.2 MPa for 20 h	Color difference ( $\Delta E$ )	TP and CR
Cokic et al.	2020	2 <sup>nd</sup> and 3 <sup>rd</sup> generations	3Y-TZP: CEREC Zirconia medi S (Dentsply Sirona), Incoris TZi (Dentsply Sirona) 5Y-TZP: Katana STML (Kuraray Noritake Dental)	134°C and 0.2 MPa for 60 h	—	TP and CR
Lopes et al.	2020	2 <sup>nd</sup> generation	3Y-TZP: Zpex (Tosoh)	134°C and 0.2 MPa for 20 h	Color difference ( $\Delta E$ )	TP and CR

TP: translucency parameter; CR: contrast ratio.

TABLE 2: Risk of bias in included studies.

Author	Publication year	Sample size calculation	Randomization	Aging protocol	Statistical analysis	Ceramic sintering	Blinded examiner	Risk of bias
Fathy et al.	2015	N	N	Y	Y	Y	N	Medium
Nakamura et al.	2016	N	N	Y	Y	Y	N	Medium
Alghazzawi TF	2017	N	N	Y	Y	Y	N	Medium
Putra et al.	2017	N	N	Y	Y	Y	N	Medium
Rafeal et al.	2018	N	N	Y	Y	N	N	High
Kim and Kim	2019	N	N	Y	Y	N	N	High
Walczak et al.	2019	N	N	Y	Y	Y	N	Medium
Kou et al.	2019	N	Y	Y	Y	Y	N	Low
Shen et al.	2020	N	N	Y	Y	Y	N	Medium
Benalcazar Jalkh et al.	2020	N	Y	Y	Y	Y	N	Low
de Araújo-Júnior et al.	2020	N	N	Y	Y	Y	N	Medium
Cokic et al.	2020	N	N	Y	Y	Y	N	Medium
Lopes et al.	2020	N	N	Y	Y	Y	N	Medium

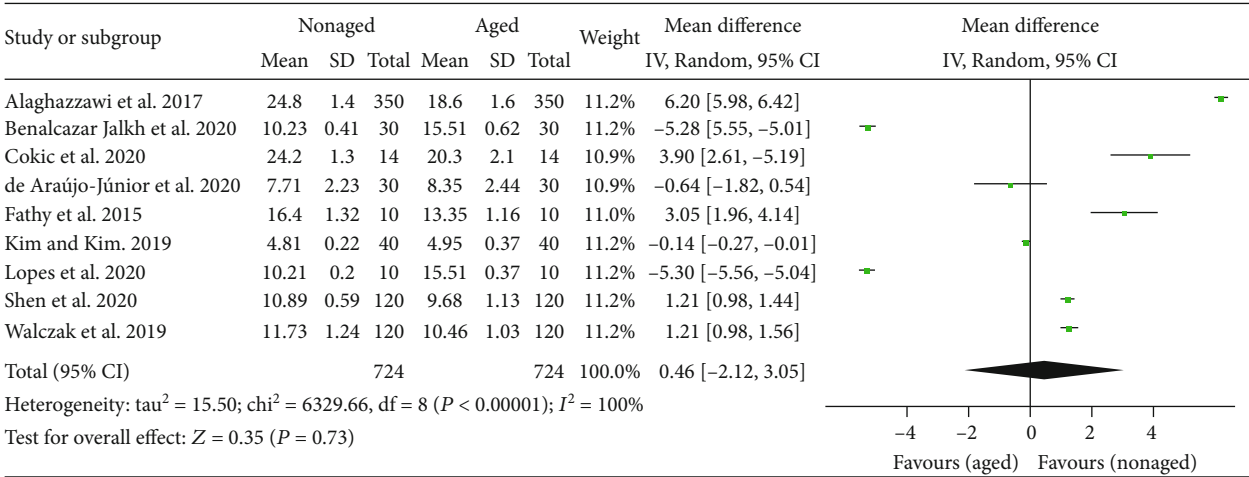


FIGURE 2: Forest plot summarizing the TP values of aged and nonaged Y-TZP ceramics. CI: confidence interval; SD: standard deviation.

analysis adopted hydrothermal aging according to the ISO 13356:2015 [55]. The simulated aging time ranged from 1 to 100 h at relatively similar temperatures (~134°C).

The results of the general meta-analysis on translucency (Figure 2) showed no significant difference in the TP value between the nonaged and aged Y-TZP ( $P = .73$ ; mean difference (MD) = 0.46; 95% confidence interval (CI) = - 2.12 to 3.05).

The results of the general meta-analysis on the  $L^*$  values showed no significant difference in the  $L^*$  value between the nonaged and aged Y-TZP ( $P = .49$ ; MD = -1.75; 95%CI = -3.25 to 6.75) (Figure 3). In the general meta-analysis of  $a^*$  values, the results showed a significant difference in the  $a^*$  value between the nonaged and aged Y-TZP ( $P = .03$ ; MD = -0.26; 95%CI = -0.51 to -0.02), favoring the nonaged Y-TZP (Figure 4). In the general meta-analysis of  $b^*$  values (Figure 5), no significant difference in the  $b^*$  value between the nonaged and aged Y-TZP was found ( $P = .62$ ; MD = 0.40; 95%CI = -1.17 to 1.97).

Subgroup analyses considering the steam autoclave duration ( $\leq 20$  h vs.  $> 20$  h) were performed on the translucency and CIE  $L^*a^*b^*$  coordinate data (Supplemental Figures 1, 2, 3, and 4). The results revealed that the steam autoclave duration contributed to the changes in the translucency and color of the aged Y-TZP ceramics ( $P$  all  $< .05$ ). When the aging duration was  $\leq 20$  h, no significant differences in the TP,  $L^*$ , and  $b^*$  values were found between aged and nonaged Y-TZP ceramics ( $P$  all  $> .05$ ). However, when the aging duration was  $> 20$  h, significant differences in the TP,  $L^*$ , and  $b^*$  values were found between the aged and nonaged Y-TZP ceramics ( $P$  all  $< .05$ ). Significantly greater  $a^*$  values were found in the aged Y-TZP ceramics than the nonaged ones, regardless of the aging duration. Furthermore, a subgroup analysis considering the type of monolithic translucent Y-TZP ceramic (3Y-TZP vs. 5Y-TZP) was performed on the translucency data (Supplemental Figure 5). No significant differences in the TP values were found between the subgroups ( $P = .45$ ).



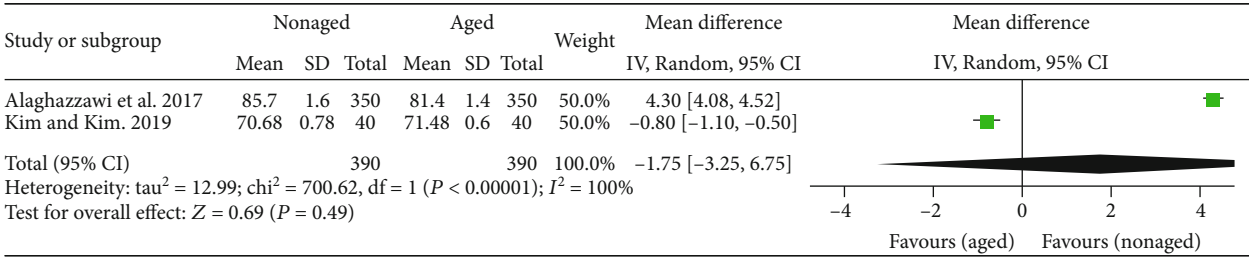


FIGURE 3: Forest plot summarizing the L\* values of aged and nonaged Y-TZP ceramics. CI: confidence interval; SD: standard deviation.

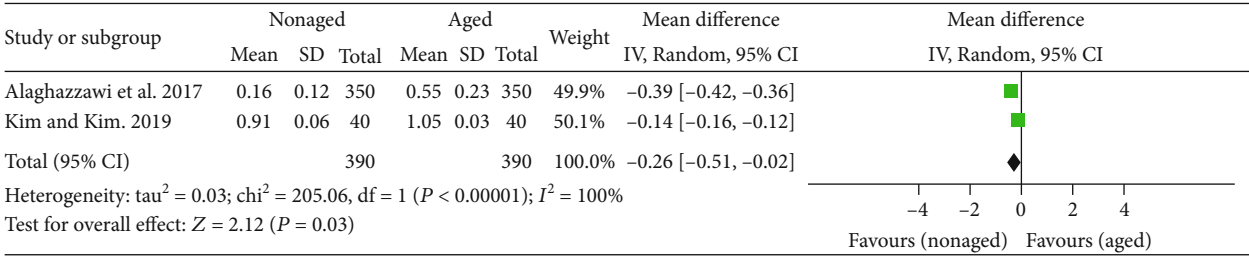


FIGURE 4: Forest plot summarizing the a\* values of aged and nonaged Y-TZP ceramics. CI: confidence interval; SD: standard deviation.

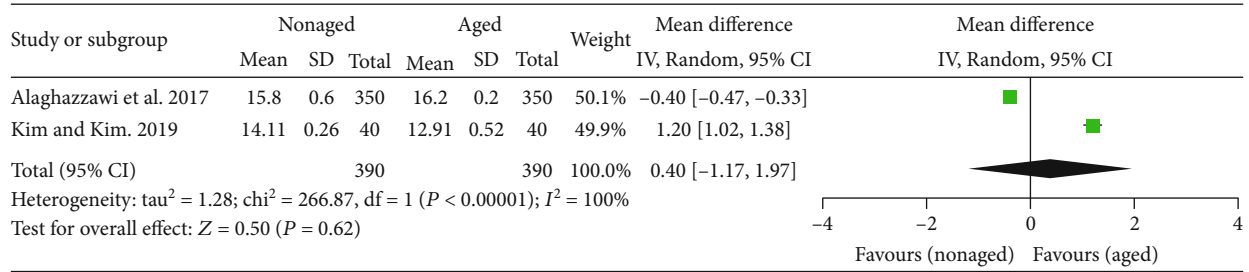


FIGURE 5: Forest plot summarizing the b\* values of aged and nonaged Y-TZP ceramics. CI: confidence interval; SD: standard deviation.

4. Discussion

To avoid the chipping of layered restorations, monolithic restorations have been promoted [1]. Monolithic restorations made of translucent Y-TZP ceramics, such as 3Y-TZP and 5Y-TZP, have become popular in recent decades. However, exposing Y-TZP ceramics directly to the oral environment may make them more susceptible to aging [16]. Therefore, this systematic review and meta-analysis was conducted to evaluate the effects of aging on the optical properties of monolithic translucent Y-TZP ceramics and can be considered the first in this study area.

In general, the esthetic outcome of monolithic Y-TZP restorations is mostly dependent on optical properties, including color and translucency. Translucency can be described as the quality of light passing through a material; this aspect is essential to the esthetic performance of dental restorations, which is crucial when selecting a restorative material [27]. The material brand, thickness, and composition (e.g., the yttrium content) have been reported to influence the optical properties of Y-TZP ceramics [56]. Other influencing factors may include the type and quantity of additives, the color shade, the coloring protocol (e.g., preco-

lored or colored by immersion in coloring liquids), the presence of *c* phase content, the sintering temperature and time, and the surface roughness [34–36].

The TP and contrast ratio (CR) have been widely used to describe the translucency of dental materials [27]. Although the CR values were not considered in the present study due to insufficient data, the TP values have been confirmed to highly correlate with the CR values, and they can be used interchangeably [25–27]. The TP values of Y-TZP ceramics remained stable when the duration of hydrothermal aging was ≤20 h. However, after hydrothermal aging for >20 h (for the included studies, 40 to 100 h), the mean ΔTP value was 5.05, indicating that the Y-TZP ceramics had become significantly more opaque. Liu et al. [57] concluded that a CR difference (ΔCR) of 0.07 is the human perception threshold for translucency. Based on the correlation established between the TP and CR values, a ΔCR of 0.07 could be transformed into a ΔTP value of 2 [58]. Therefore, the translucency changes due to aging detected in the present study might be perceived by visual assessments. The change in translucency during aging is probably associated with the transformation of zirconia from the *t* phase to the *m* phase [40]. An increase in the *m* phase content due to aging causes

the formation of microcracks and increases the surface porosity, therefore increasing the surface roughness, light scattering, and reflection [11–13]. The coexistence of the  $t$  and  $m$  phases after aging may also contribute to an increase in the difference in the refractive indices for an incident light beam, thereby decreasing the translucency [35, 59, 60]. The longer the aging duration is, the greater the  $t$ -to- $m$  phase transformation (greater  $m$  phase content). An increase in the  $m$  phase content has been proposed to lead to increased opacity due to the abovementioned reasons [16, 61].

The color difference ( $\Delta E$ ) between 2 subjects can be calculated and used to report relative color changes. In dentistry, a  $\Delta E$  of 2.7 is considered the threshold for a clinically unacceptable color difference according to ISO/TR 28642:2016 [44]. Apart from  $\Delta E$  values, the National Bureau of Standards (NBS) units (NBS units =  $\Delta E \times 0.92$ ) are also regarded as a means of visual assessment [62]. Significant differences in the  $a^*$  values between the aged and nonaged Y-TZP ceramics were found, indicating that the Y-TZP ceramics appeared more reddish (greater  $a^*$ ) after aging. According to the meta-analysis, the mean  $\Delta L^*$ ,  $\Delta a^*$ , and  $\Delta b^*$  values were -1.75, -0.26, and 0.40, respectively. Based on the equation  $\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2}$  [63],  $\Delta E = 1.81$ , and NBS unit = 1.67, indicating that the color changes caused by aging might be noticeable. Similar to the TP values, the hydrothermal aging duration contributed to the changes in the CIE  $L^*$ ,  $a^*$ , and  $b^*$  values. The color (CIE  $L^*$ ,  $a^*$ , and  $b^*$  values) of the aged monolithic translucent zirconia remained unchanged when the aging duration  $\leq 20$  h. When the Y-TZP ceramics were aged for more than 20 h (for the included studies, 40 to 100 h), the  $\Delta E = 5.73$ , indicating that the color changes were clinically unacceptable. Theoretically, thermal conditions may have an effect on the coloring pigments added to Y-TZP ceramics, causing pigment breakdown and resulting in color instability [64]. For example, some of the monolithic zirconia consists of minute amount of  $\text{Fe}_2\text{O}_3$  as the pigment [65].  $\text{Fe}_2\text{O}_3$  has at least three isomorphs ( $\alpha$ ,  $\gamma$ , and  $\epsilon$ ) whereas they have different observable band gaps and oxygen valencies, such that  $\alpha$  and  $\gamma$  are easily interchanged with each other even at room temperature [66]. Nevertheless, the exact mechanism of color instability is not clear and requires further investigation. In addition, the breakdown of colorants could also affect TP which was shown to be related to the changes in lightness and yellow-blue coordinates [67]. Thus, color is an important perceptive factor in the determination of the TP, given that TP is determined by the colorimeter/spectrophotometer and the thickness of the specimen tested. In other words, the experimental operating condition is critical and should receive more attention in the literature [27, 50].

Although hydrothermal aging is the most common method of accelerated aging, other less aggressive aging methods, such as thermocycling and exposure to ultraviolet light and water spray in a weathering machine, were used in the literature [23, 38]. Compared with steam autoclave, less aggressive aging methods, such as thermocycling and exposure to ultraviolet light and water spray in a weathering machine, presented less pronounced effects on the optical

properties of Y-TZP ceramics. Dikicier et al. [23] reported that aging in a weathering machine for 300 h is equivalent to 1 year of clinical service. After 200 h of aging in a weathering machine, the Y-TZP ceramic presented only a minor color change, with a mean  $\Delta E$  value of 1.19. Papageorgiou-Kyranas et al. [38] concluded that monolithic Y-TZP, either precolored or colored by immersion in staining solutions, can be considered color stable after 5000 thermocycles.

Although sensitivity analyses were conducted, no particular studies were responsible for generating heterogeneity. The high heterogeneity observed in the analyses could be explained by the various brands of test materials and the aging protocols, which may have led to a large change in the aging behavior. The present study was considered to have the following limitations: no subgroup analyses considering the type of Y-TZP ceramic on CIE  $L^*a^*b^*$  coordinate data were performed because of insufficient data. Although the risk of bias assessment was based on previous studies [46, 47], the assessment methods may be improved by considering the topic of bias. Moreover, no clinical studies in this field were found; thus, there is weak evidence to support clinical recommendations.

Based on the present findings, the optical properties of monolithic translucent Y-TZP ceramics seemed to be stable after hydrothermal aging at 134°C and 0.2 MPa for  $\leq 20$  h. Clinically unacceptable changes in the translucency and color of monolithic translucent Y-TZP ceramics were found after hydrothermal aging for  $>20$  h. The general consensus is that 1 h of autoclave aging is equivalent to 3 to 4 years *in vivo* [15], although a recent study reported that aging at 134°C and 0.2 MPa for 5 h was considered equivalent to 2 years of aging *in vivo* [24]. However, it is important to emphasize that *in vivo* data are needed to correlate the data from laboratory simulations and clinical situations. Therefore, further clinical studies are needed to clarify this hypothesis.

## 5. Conclusions

Within the limitations of this study, the following conclusions may be drawn:

- (1) The translucency and color of monolithic translucent Y-TZP ceramics remained stable when the duration of hydrothermal aging was less than 20 h.
- (2) Clinically unacceptable changes in the translucency and color of monolithic translucent Y-TZP ceramics were found when the duration of hydrothermal aging was more than 20 h.

## Data Availability

The data supporting the present results are included in this article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

This work was partially supported by the Fujian Provincial Health Technology Project, China (No. 2019-CX-32), and the Startup Fund for Scientific Research, Fujian Medical University, China (No. 2017XQ1112).

## Supplementary Materials

Supplemental Table 1: search terms and combinations used in the literature search. Supplemental Figure 1: forest plot summarizing TP values of aged and nonaged Y-TZP ceramics (subgroup: steam autoclave duration). CI: confidence interval; SD: standard deviation. Supplemental Figure 2: forest plot summarizing L\* values of aged and nonaged Y-TZP ceramics (subgroup: steam autoclave duration). CI: confidence interval; SD: standard deviation. Supplemental Figure 3: forest plot summarizing a\* values of aged and nonaged Y-TZP ceramics (subgroup: steam autoclave duration). CI: confidence interval; SD: standard deviation. Supplemental Figure 4: forest plot summarizing b\* values of aged and nonaged Y-TZP ceramics (subgroup: steam autoclave duration). CI: confidence interval; SD: standard deviation. Supplemental Figure 5: forest plot summarizing TP values of aged and nonaged Y-TZP ceramics (subgroup: type of Y-TZP ceramic). CI: confidence interval; SD: standard deviation. (*Supplementary materials*)

## References

- [1] C. Agingu, C. Zhang, N. Jiang, H. Cheng, M. Ozcan, and H. Yu, "Intraoral repair of chipped or fractured veneered zirconia crowns and fixed dental prosthesis: clinical guidelines based on literature review," *Journal of Adhesion Science and Technology*, vol. 32, no. 15, pp. 1711–1723, 2018.
- [2] Y. Zhang and B. R. Lawn, "Novel zirconia materials in dentistry," *Journal of Dental Research*, vol. 97, no. 2, pp. 140–147, 2018.
- [3] S. K. Makhija, N. C. Lawson, G. H. Gilbert et al., "Dentist material selection for single-unit crowns: findings from the National Dental Practice-Based Research Network," *Journal of Dentistry*, vol. 55, pp. 40–47, 2016.
- [4] I. Denry and J. Kelly, "State of the art of zirconia for dental applications," *Dental Materials*, vol. 24, no. 3, pp. 299–307, 2008.
- [5] C. Agingu, N.-w. Jiang, H. Cheng, and H. Yu, "Effect of Different Coloring Procedures on the Aging Behavior of Dental Monolithic Zirconia," *Journal of Spectroscopy*, vol. 2018, Article ID 2137091, 7 pages, 2018.
- [6] A. Han, J. K. H. Tsoi, J. P. Matinlinna, Y. Zhang, and Z. Chen, "Effects of different sterilization methods on surface characteristics and biofilm formation on zirconia \_in vitro\_," *Dental Materials*, vol. 34, no. 2, pp. 272–281, 2018.
- [7] M. Sedda, A. Vichi, M. Carrabba, A. Capperucci, C. Louca, and M. Ferrari, "Influence of coloring procedure on flexural resistance of zirconia blocks," *The Journal of Prosthetic Dentistry*, vol. 114, no. 1, pp. 98–102, 2015.
- [8] F. Zhang, M. Inokoshi, M. Batuk et al., "Strength, toughness and aging stability of highly-translucent Y-TZP ceramics for dental restorations," *Dental Materials*, vol. 32, no. 12, pp. e327–e337, 2016.
- [9] G. K. R. Pereira, C. Muller, V. F. Wandscher, M. P. Rippe, C. J. Kleverlaan, and L. F. Valandro, "Comparison of different low-temperature aging protocols: its effects on the mechanical behavior of Y-TZP ceramics," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 60, pp. 324–330, 2016.
- [10] M. Cattani-Lorente, S. S. Scherrer, P. Ammann, M. Jobin, and H. W. A. Wiskott, "Low temperature degradation of a Y-TZP dental ceramic," *Acta Biomaterialia*, vol. 7, no. 2, pp. 858–865, 2011.
- [11] T. J. Lucas, N. C. Lawson, G. M. Janowski, and J. O. Burgess, "Effect of grain size on the monoclinic transformation, hardness, roughness, and modulus of aged partially stabilized zirconia," *Dental Materials*, vol. 31, no. 12, pp. 1487–1492, 2015.
- [12] M. Inokoshi, K. Vanmeensel, F. Zhang et al., "Aging resistance of surface-treated dental zirconia," *Dental Materials*, vol. 31, no. 2, pp. 182–194, 2015.
- [13] S. M. Fathy, A. A. El-Fallal, S. A. El-Negoly, and A. B. El Bedawy, "Translucency of monolithic and core zirconia after hydrothermal aging," *Acta Biomater Odontol Scand*, vol. 1, no. 2–4, pp. 86–92, 2015.
- [14] I. C. Clarke, M. Manaka, D. D. Green et al., "Current Status Of Zirconia Used in Total Hip Implants," *The Journal of Bone and Joint Surgery-American Volume*, vol. 85, pp. 73–84, 2003.
- [15] S. Ramesh, K. Y. S. Lee, and C. Y. Tan, "A review on the hydrothermal ageing behaviour of Y-TZP ceramics," *Ceramics International*, vol. 44, no. 17, pp. 20620–20634, 2018.
- [16] V. Lughi and V. Sergo, "Low temperature degradation -aging- of zirconia: a critical review of the relevant aspects in dentistry," *Dental Materials*, vol. 26, no. 8, pp. 807–820, 2010.
- [17] G. M. De Souza, A. Zyklus, R. R. Ghahnavyeh, S. K. Lawrence, and D. F. Bahr, "Effect of accelerated aging on dental zirconia-based materials," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 65, pp. 256–263, 2017.
- [18] G. K. R. Pereira, A. B. Venturini, T. Silvestri et al., "Low-temperature degradation of Y-TZP ceramics: a systematic review and meta- analysis," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 55, pp. 151–163, 2015.
- [19] F. F. Lange, G. L. Dunlop, and B. I. Davis, "Degradation during aging of transformation-toughened ZrO<sub>2</sub>-Y<sub>2</sub>O<sub>3</sub> materials at 250°C," *Journal of the American Ceramic Society*, vol. 69, no. 3, pp. 237–240, 1986.
- [20] P. Pandoleon, E. Kontonasaki, N. Kantiranis et al., "Aging of 3Y-TZP dental zirconia and yttrium depletion," *Dental Materials*, vol. 33, no. 11, pp. e385–e392, 2017.
- [21] P. E. Spyropoulou, P. Kamposiora, G. Eliades, G. Papavasiliou, M. E. Razzoog, and S. C. Bayne, "Cyclic loading effect on color stability of unshaded versus shaded zirconia," *Journal of Esthetic and Restorative Dentistry*, vol. 28, no. 2, pp. 77–84, 2016.
- [22] H. K. Kim and S. H. Kim, "Effect of hydrothermal aging on the optical properties of precolored dental monolithic zirconia ceramics," *The Journal of Prosthetic Dentistry*, vol. 121, no. 4, pp. 676–682, 2019.
- [23] S. Dikicier, S. Ayyildiz, J. Ozen, and C. Sipahi, "Effect of varying core thicknesses and artificial aging on the color difference of different all-ceramic materials," *Acta Odontologica Scandinavica*, vol. 72, no. 8, pp. 623–629, 2014.
- [24] M. Cattani-Lorente, S. Durual, M. Amez-Droz, H. W. A. Wiskott, and S. S. Scherrer, "Hydrothermal degradation of a 3Y-TZP translucent dental ceramic: A comparison of

- numerical predictions with experimental data after 2 years of aging,” *Dental Materials*, vol. 32, no. 3, pp. 394–402, 2016.
- [25] T. F. Alghazzawi, “The effect of extended aging on the optical properties of different zirconia materials,” *Journal of Prosthodontic Research*, vol. 61, no. 3, pp. 305–314, 2017.
  - [26] B. Yu, J. S. Ahn, and Y. K. Lee, “Measurement of translucency of tooth enamel and dentin,” *Acta Odontologica Scandinavica*, vol. 67, no. 1, pp. 57–64, 2009.
  - [27] W. M. Johnston, “Review of translucency determinations and applications to dental materials,” *Journal of Esthetic and Restorative Dentistry*, vol. 26, no. 4, pp. 217–223, 2014.
  - [28] K. Harada, A. Shinya, H. Gomi, Y. Hatano, A. Shinya, and A. J. Raigrodski, “Effect of accelerated aging on the fracture toughness of zirconias,” *The Journal of Prosthetic Dentistry*, vol. 115, no. 2, pp. 215–223, 2016.
  - [29] Y. A. Mota, C. Cotes, R. F. Carvalho et al., “Monoclinic phase transformation and mechanical durability of zirconia ceramic after fatigue and autoclave aging,” *Journal of Biomedical Materials Research. Part B, Applied Biomaterials*, vol. 105, no. 7, pp. 1972–1977, 2017.
  - [30] L. F. Guilardi, G. K. R. Pereira, A. Gundel, M. P. Rippe, and L. F. Valandro, “Surface micro-morphology, phase transformation, and mechanical reliability of ground and aged monolithic zirconia ceramic,” *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 65, pp. 849–856, 2017.
  - [31] P. A. Pinto, G. Colas, T. Filleter, and G. M. De Souza, “Surface and mechanical characterization of dental yttria-stabilized tetragonal zirconia polycrystals (3Y-TZP) after different aging processes,” *Microscopy and Microanalysis*, vol. 22, no. 6, pp. 1179–1188, 2016.
  - [32] T. J. Lucas, N. C. Lawson, G. M. Janowski, and J. O. Burgess, “Phase transformation of dental zirconia following artificial aging,” *Journal of Biomedical Materials Research. Part B, Applied Biomaterials*, vol. 103, no. 7, pp. 1519–1523, 2015.
  - [33] H. Yang, Y. L. Xu, G. Hong, and H. Yu, “Effects of low-temperature degradation on the surface roughness of yttria-stabilized tetragonal zirconia polycrystal ceramics: A systematic review and meta-analysis,” *The Journal of Prosthetic Dentistry*, 2020.
  - [34] L. Jiang, Y. Liao, Q. Wan, and W. Li, “Effects of sintering temperature and particle size on the translucency of zirconium dioxide dental ceramic,” *Journal of Materials Science. Materials in Medicine*, vol. 22, no. 11, pp. 2429–2435, 2011.
  - [35] Y. Zhang, “Making yttria-stabilized tetragonal zirconia translucent,” *Dental Materials*, vol. 30, no. 10, pp. 1195–1203, 2014.
  - [36] B. Stawarczyk, A. Emslander, M. Roos, B. Sener, F. Noack, and C. Keul, “Zirconia ceramics, their contrast ratio and grain size depending on sintering parameters,” *Dental Materials Journal*, vol. 33, no. 5, pp. 591–598, 2014.
  - [37] C. F. Rafael, P. F. Cesar, M. Fredel, R. de Souza Magini, A. Liebermann, and C. A. M. Volpato, “Impact of laboratory treatment with coloring and fluorescent liquids on the optical properties of zirconia before and after accelerated aging,” *The Journal of Prosthetic Dentistry*, vol. 120, no. 2, pp. 276–281, 2018.
  - [38] A. Papageorgiou-Kyrana, M. Kokoti, E. Kontonasaki, and P. Koidis, “Evaluation of color stability of preshaded and liquid-shaded monolithic zirconia,” *The Journal of Prosthetic Dentistry*, vol. 119, no. 3, pp. 467–472, 2018.
  - [39] T. Nakamura, Y. Nakano, H. Usami et al., “Translucency and low-temperature degradation of silica-doped zirconia: A pilot study,” *Dental Materials Journal*, vol. 35, no. 4, pp. 571–577, 2016.
  - [40] K. Walczak, H. Meißner, U. Range et al., “Translucency of Zirconia Ceramics before and after Artificial Aging,” *Journal of Prosthodontics*, vol. 28, no. 1, pp. e319–e324, 2019.
  - [41] A. Putra, K. H. Chung, B. D. Flinn et al., “Effect of hydrothermal treatment on light transmission of translucent zirconias,” *The Journal of Prosthetic Dentistry*, vol. 118, no. 3, pp. 422–429, 2017.
  - [42] K. Papageorgiou-Kyrana, M. Fasoula, and E. Kontonasaki, “Translucency of monolithic zirconia after hydrothermal aging: a review of in vitro studies,” *Journal of Prosthodontics*, vol. 29, no. 6, pp. 489–500, 2020.
  - [43] D. Moher, A. Liberati, J. Tetzlaff, D. G. Altman, and for the PRISMA Group, “Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement,” *BMJ*, vol. 339, no. jul21 1, p. b2535, 2009.
  - [44] International Standard ISO/TR 28642:2016, *Dentistry-guidance on colour measurement*, Geneva, Switzerland, 2016, 2nd Edition.
  - [45] H. Yu, Y. H. Chen, H. Cheng, and T. Sawase, “Finish-line designs for ceramic crowns: a systematic review and meta-analysis,” *The Journal of Prosthetic Dentistry*, vol. 122, no. 1, pp. 22–30.e5, 2019.
  - [46] R. Sarkis-Onofre, J. A. Skupien, M. S. Cenci, R. R. Moraes, and T. Pereira-Cenci, “The role of resin cement on bond strength of glass-fiber posts luted into root canals: a systematic review and meta-analysis of in vitro studies,” *Operative Dentistry*, vol. 39, no. 1, pp. E31–E44, 2014.
  - [47] H. Yu, M. Ozcan, K. Yoshida, H. Cheng, and T. Sawase, “Bonding to industrial indirect composite blocks: a systematic review and meta-analysis,” *Dental Materials*, vol. 36, no. 1, pp. 119–134, 2020.
  - [48] J. P. Higgins, J. J. Deeks, and D. G. Altman, “Chapter 16: Special topics in statistics,” *Cochrane Handbook for Systematic Reviews of Interventions Version 5.1.0. The Cochrane Collaboration*, J. P. Higgins and S. Green, Eds., 2011, Available from <http://handbook.cochrane.org/>.
  - [49] W. Kou, K. Garbriellsson, A. Borhani, M. Carlborg, and M. M. Thorén, “The effects of artificial aging on high translucent zirconia,” *Biomaterial Investigations in Dentistry*, vol. 6, no. 1, pp. 54–60, 2019.
  - [50] J. Shen, H. Xie, X. Wu, J. Yang, M. Liao, and C. Chen, “Evaluation of the effect of low-temperature degradation on the translucency and mechanical properties of ultra-transparent 5Y-TZP ceramics,” *Ceramics International*, vol. 46, no. 1, pp. 553–559, 2020.
  - [51] E. B. B. Jalkh, K. N. Monteiro, P. F. Cesar et al., “Aging resistant ZTA composite for dental applications: Microstructural, optical and mechanical characterization,” *Dental Materials*, vol. 36, no. 9, pp. 1190–1200, 2020.
  - [52] S. M. Cokic, J. Vleugels, B. Van Meerbeek et al., “Mechanical properties, aging stability and translucency of speed-sintered zirconia for chairside restorations,” *Dental Materials*, vol. 36, no. 7, pp. 959–972, 2020.
  - [53] E. N. S. de Araújo-Júnior, E. T. P. Bergamo, T. M. B. Campos et al., “Hydrothermal degradation methods affect the properties and phase transformation depth of translucent zirconia,” *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 112, p. 104021, 2020.



- [54] A. C. O. Lopes, P. G. Coelho, L. Witek et al., "Microstructural, mechanical, and optical characterization of an experimental aging-resistant zirconia-toughened alumina (ZTA) composite," *Dental Materials*, vol. 36, no. 12, pp. e365–e374, 2020.
- [55] International Standard ISO 13356:2015, *Implants for surgery. Ceramic materials based on yttria-stabilized tetragonal zirconia (Y-TZP)*, Geneva, Switzerland, 2015, 3rd Edition.
- [56] S. Kurtulmus-Yilmaz and M. Ulusoy, "Comparison of the translucency of shaded zirconia all-ceramic systems," *J Adv Prosthodont*, vol. 6, no. 5, pp. 415–422, 2014.
- [57] M. C. Liu, S. A. Aquilino, P. S. Lund et al., "Human perception of dental porcelain translucency correlated to spectrophotometric measurements," *Journal of Prosthodontics*, vol. 19, no. 3, pp. 187–193, 2010.
- [58] Y. K. Lee, "Criteria for clinical translucency evaluation of direct esthetic restorative materials," *Restor Dent Endod*, vol. 41, no. 3, pp. 159–166, 2016.
- [59] E. A. McLaren and D. A. Terry, "CAD/CAM systems, materials, and clinical guidelines for all-ceramic crowns and fixed partial dentures," *The Compendium of Continuing Education in Dentistry*, vol. 23, pp. 637–647, 2002.
- [60] M. J. Heffernan, S. A. Aquilino, A. M. Diaz-Arnold, D. R. Haselton, C. M. Stanford, and M. A. Vargas, "Relative translucency of six all-ceramic systems. Part I: core materials," *The Journal of Prosthetic Dentistry*, vol. 88, no. 1, pp. 4–9, 2002.
- [61] M. T. Hernandez, J. R. Jurado, P. Duran, and J. L. G. Fierro, "Subeutectoid degradation of yttria-stabilized tetragonal zirconia polycrystal and ceria-doped yttria-stabilized tetragonal zirconia polycrystal ceramics," *Journal of the American Ceramic Society*, vol. 74, no. 6, pp. 1254–1258, 1991.
- [62] T. Koksall and I. Dikbas, "Color stability of different denture teeth materials against various staining agents," *Dental Materials Journal*, vol. 27, no. 1, pp. 139–144, 2008.
- [63] N. Jiang, C. Zhang, C. Agingu, T. Attin, H. Cheng, and H. Yu, "Comparison of whitening dentifrices on the effectiveness of in-office tooth bleaching: a double-blind randomized controlled clinical trial," *Operative Dentistry*, vol. 44, no. 2, pp. 138–145, 2019.
- [64] F. Gonuldas, K. Yilmaz, and C. Ozturk, "The effect of repeated firings on the color change and surface roughness of dental ceramics," *J Adv Prosthodont*, vol. 6, no. 4, pp. 309–316, 2014.
- [65] T. A. Sulaiman, A. A. Abdulmajeed, K. Shahramian, and L. Lassila, "Effect of different treatments on the flexural strength of fully versus partially stabilized monolithic zirconia," *The Journal of Prosthetic Dentistry*, vol. 118, no. 2, pp. 216–220, 2017.
- [66] M. de Ridder, P. C. van de Ven, R. G. van Welzenis et al., "Growth of Iron Oxide on Yttria-Stabilized Zirconia by Atomic Layer Deposition," *The Journal of Physical Chemistry B*, vol. 106, no. 51, pp. 13146–13153, 2002.
- [67] C. Gasparik, A. V. Burde, A. G. Grecu, I. Chiorean, D. Dudea, and M. E. Badea, "The influence of color parameters on the translucency of ceramic material," *J Optoelectron Advanced Materials*, vol. 9, pp. 241–242, 2015.