International Journal of Biomedicine 14(3) (2024) 503-509
http://dx.doi.org/10.21103/Article14(3)_OA19

INTERNATIONAL JOURNAL OF BIOMEDICINE

ORIGINAL ARTICLE

Dentistry

Hardness and Density of Conventional and Monolithic Zirconia after Sintering

Genc Rukiqi[1], Kujtim Shala[2*], Teuta Pustina[2], Fisnik Aliaj[3], Erik Musliu[4], Mirjet Lushaj[5]

[1]Department of Prosthodontics, AMECC "Rezonanca," Pristina, Republic of Kosovo
[2]Department of Prosthodontics, University of Prishtina "Hasan Prishtina" Pristina, Republic of Kosovo
[3]Department of Physics, Faculty of FMNS, University of Prishtina "Hasan Prishtina" Pristina, Republic of Kosovo
[4]Department of Dentistry, AMECC "Rezonanca," Pristina, Republic of Kosovo
[5]Advanced Dental Center – Clinic and Dental Lab, Pristina, Republic of Kosovo

Abstract

Background: Zirconia (zirconium dioxide, ZrO_2) has optimum properties for dental use. Its main advantages include biocompatibility, biomechanical stability, and high fracture resistance. This in vitro study aimed to determine and compare the hardness and density of conventional and monolithic zirconium after the laboratory sintering process.

Methods and Results: This experimental-comparative study was carried out on processed samples of zirconia blocks, determining their mechanical properties and comparing them between different zirconia materials. Conventional zirconia blocks (from Dentsply Sirona Cercon HT and Orodent Zirconia HT) and monolithic zirconium blocks (from Dentsply Sirona Cercon ML and Orodent Zirconia Thor) were processed to produce 80 molar crowns. Samples were divided into two groups: Sirona[S]–Orodent[O]/Conventional [C] group (n=40) and Sirona[S]–Orodent[O]/Monolithic [M] group (n=40). Sirona samples were divided into Sirona-Conventional (SC) subgroup (n=20) and Sirona-Monolithic (SM) subgroup (n=20); Orodent samples were divided into Orodent-Conventional (OC) subgroup (n=20) and Orodent-Monolithic (OM) subgroup (n=20). Samples were formed with an occlusal thickness of 2 mm and were sintered at 1450 °C for 2 hours. Hardness expressed in Vickers Hardness Number (VHN) was performed using a microhardness tester (Model HV-1000DT), and density determination (g/cm^3) was performed with a pycnometer. The results showed no significant differences (P=0.137) between the Sirona manufacturer's SC and SM subgroups. The subgroups of the Orodent manufacturer showed statistically significant differences: the OM subgroup had a higher hardness value than the OS subgroup (1654.95±140.731 VHN versus 1526.45±149.011 VHN, P=0.008). Among the four studied subgroups, the highest hardness was in the OM subgroup (1654.95±140.731 VHN) compared to the SC subgroup (1595.55±147.790 VHN), OC subgroup (1526.45±149.011 VHN), and SM subgroup (1525.95±142.081 VHN) (P=0.016). Density in the subgroups SC, OC, SM, and OM was 6.246 g/cm^3, 6.081g/cm^3, 6.217 g/cm^3, and 6.187 g/cm^3, respectively, without statistically significant differences (P>0.05).

Conclusion: The findings highlight the suitability of both zirconia materials from Dentsply Sirona and Orodent manufacturers for dental restorations, with Orodent monolithic zirconia offering potential advantages in terms of hardness.**(International Journal of Biomedicine. 2024;14(3):503-509.)**

Keywords: conventional zirconia • density • hardness • monolithic zirconia • sintering

For citation: Rukiqi G, Shala K, Pustina T, Aliaj F, Musliu E, Lushaj M. Hardness and Density of Conventional and Monolithic Zirconia after Sintering. International Journal of Biomedicine. 2024;14(3):503-509. doi:10.21103/Article14(3)_OA19

Abbreviations

CAD, computer-aided design; **CAM**, computer-aided manufacturing; **LTD**, low-temperature degradation; **VHN**, Vickers hardness number; **Y-TZP**, yttrium-stabilized tetragonal zirconia polycrystal.

Introduction

Currently, the most popular dental ceramic systems are silica-based, leucite-based, lithium disilicate-based, alumina-based, and zirconia-based materials. Zirconia (zirconium dioxide, ZrO_2), also known as "ceramic steel," has optimum properties for dental use.[1]

Among the ceramic materials used in the fabrication of crowns, yttrium-stabilized tetragonal zirconia polycrystal (Y-TZP) is further explored by having greater mechanical properties with a success that depends on a stable bond between zirconia and teeth,[2] with a compression resistance of about 2000 MPa and optical properties than the other ceramics.[3] For various reasons, zirconia-based ceramics are the most studied and challenging research. Recent studies have shown through histological observation that zirconia-based implants have similar osseointegration and biocompatibility to titanium implants.[4] Today, three types of zirconia systems are used: yttria-stabilized zirconia polycrystals (Y-SZP), ceria-stabilized zirconia/alumina nanocomposite (Ce-TZP/A), and magnesia partially stabilized zirconia (Mg-PSZ).[5]

Yttrium-stabilized tetragonal zirconia polycrystal (Y-TZP), one of the most common dental zirconia modifications, has higher mechanical properties and better resistance to various oral factors that can affect the material than other regular ceramic masses.[1] Adding small percentages of yttria (3 mol%) stabilizes the crystal structure transformation during firing at elevated temperatures and improves the physical properties of zirconia.[6] Zirconia occurs in three phases: monoclinic (m), cubic (c), and tetragonal.[7] Unlike glass ceramics, zirconia is acid-resistant polycrystalline with no glass-content microstructure.[8] As the demand for aesthetics in dental practice increases and technology evolves, the reproduction of lifelike opalescence, fluorescence, and translucency is required to mimic the appearance of a natural tooth.[9] In addition, the invention of computer-aided design (CAD) and computer-aided manufacturing (CAM) technology has increased the use of zirconia. CAD/CAM technology, introduced in the dental industry in the last decade, has reduced human error in model construction and crown fabrication. This digital system continues to be updated and improved.[10] As a result, all-ceramic fixed prosthodontic restorations using zirconia as a framework have been delivered to patients with high strength and good esthetic results.[11]

Biocompatibility, biomechanical stability, and high fracture resistance are some of the main advantages of zirconia. Translucency is one of the optical properties of zirconia. With increased content in the cubic phase, translucency increases, but the mechanical properties of zirconia decrease.[12] The materials of ceramics and their mechanical properties are typically measured by different values, such as Vickers hardness, fracture toughness, Weibull modulus, and flexural strength.[13]

This study aimed to determine the hardness and density of conventional and monolithic zirconia blocks from two manufacturers. Main hypothesis 1 (H1) is that there is a significant difference between the hardness of conventional and monolithic zirconia, there is a significant difference between the density of conventional and monolithic zirconium, hypothesis 0 (H0) is that there is no significant difference between the hardness of conventional and monolithic zirconium, there is no significant difference between the density of conventional and monolithic zirconium.

Materials and Methods

This experimental-comparative study was carried out on processed samples of zirconia blocks, determining their mechanical properties and comparing them between different zirconia materials.

Specimen Preparation

Eight zirconia blocks were included in this study: four blocks of conventional zirconia and four blocks of monolithic zirconia. Of the four conventional zirconia blocks, two were from Sirona Dental CAD/CAM Cercon HT, two were from Orodent CAD/CAM SRL HT, and of the four monolithic zirconia blocks, two blocks were from Sirona Dental CAD/CAM Cercon ML, and two from Orodent CAD/CAM SRL Thor. All blocks were 98 mm in diameter and 14 mm thick. The CAD/CAM Sirona design software was used to print molar crowns in the dental laboratory. After designation, 80 molar crowns were fabricated on the Sirona CAD/CAM milling machine (Sirona inLab MC X5; Figure 1), and samples were divided into two groups: Sirona[S]–Orodent[O]/Conventional [C] group (n=40) and Sirona[S]–Orodent[O]/Monolithic [M] group (n=40). Sirona samples were divided into Sirona-Conventional (SC) subgroup (n=20) and Sirona-Monolithic (SM) subgroup (n=20); Orodent samples were divided into Orodent-Conventional (OC) subgroup (n=20) and Orodent-Monolithic (OM) subgroup (n=20).

Each sample measured 15 mm wide and 15 mm high, with a minimal occlusal thickness of 2 mm. The processed blocks were removed from the milling machine, cut, cleaned with rubber tips, and dried with dry air. All samples were sintered at a temperature of 1450 ºC for 2 hours in a sintering furnace (Sirona inFire HTC; Figure 2). The temperature increased from 20 ºC/min to 800 ºC and from 10 ºC/min to 1450 ºC. Finally, the samples were gradually cooled for 20 minutes.

Fig. 1. *Sirona inLab MC X5- milling machine*

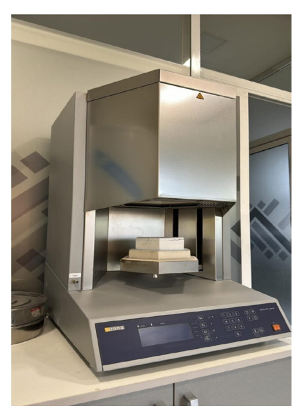

Fig. 2. *Sirona inFire HTC Speed.*

Hardness Measurement

Hardness was measured using a microhardness tester (Model HV-1000DT). When placing the sample on the microhardness tester platform, the sample was first identified through the identifying eyepiece by slowly moving the base (Figures 3 and 4).

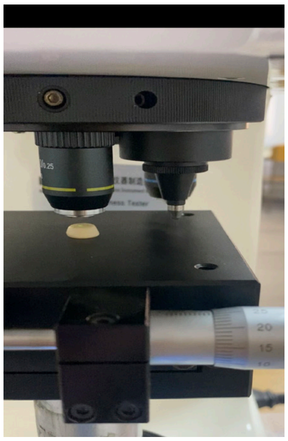

Fig. 3. *The microhardness tester and the sample.*

Fig.4. *Sample on the microhardness tester platform.*

After identifying the sample, the measuring process continued with the tracking eyepiece (indenter). Through the indenter, a load of 1 kg was applied to the sample for a duration of 10 seconds, during which the hardness measurement was taken (Figures 5 and 6). The impression is then identified through another determining eyepiece (Figure 7).

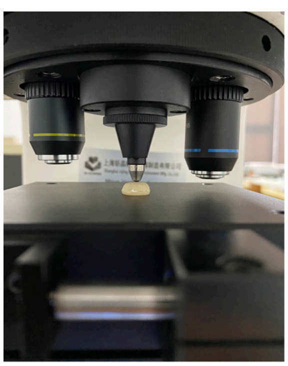

Fig. 5. *Microhardness tester during indenter impression of the molar crown.*

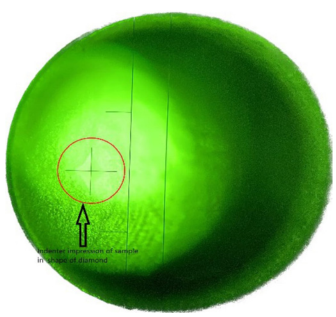

Fig. 6. *Indenter impression.*

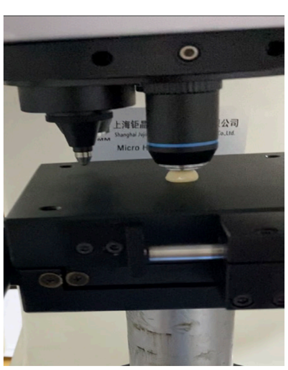

Fig. 7. *Identification of impressions by indenter and measurement.*

Using the equation $VHN = (x)\ F/d^2$, where VHN is the Vickers hardness number, F represents the loaded weight in kilograms (kg), and d is the average length of the cut diagonals in millimeters (Figures 8 and 9), the hardness expressed in VHN was determined for each sample.

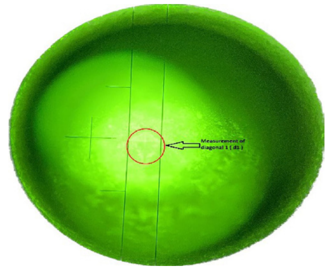

Fig. 8. *Measurement of d1 on the impression by the indenter.*

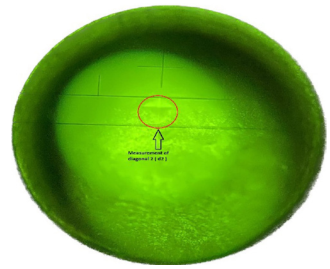

Fig. 9. *Measurement of d2 on the impression by the indenter.*

Density Measurement

A pycnometer is a device used to measure the density of a substance. First, the pycnometer was cleaned and dried thoroughly. Then, the pycnometer was filled with density liquid (water), and the volume of the liquid was recorded. Small particles were cut from the zirconia disks of each manufacturer before sintering (Sirona Conventional [SC], Sirona Monolithic [SM]), and Orodent Conventional [OC], Orodent Monolithic [OM]). They were dried and cleaned. The zirconia particles of each group were added to the pycnometer, and then the new liquid volume with the sample inside it was recorded. The volume occupied by the sample was calculated by subtracting the initial liquid volume from the liquid volume after the sample was added. The density of the sample was calculated using the following formula: $\rho=M/V$, where M is the sample mass in grams and V - volume occupied by the sample in g/cm^3.

Statistical Analysis

Statistical analysis was performed using the statistical software package SPSS version 22.0 (SPSS Inc, Armonk, NY: IBM Corp). For the descriptive analysis, results are presented as mean (M), standard deviation (SD), and standard error of the mean (SEM). Inter-group comparisons were performed using Student's t-test. Multiple comparisons were performed with one-way ANOVA. A probability value of $P<0.05$ was considered statistically significant.

Results

This study included 80 samples from two different manufacturers. Sirona samples were divided into SC and SM subgroups, and Orodent samples were divided into OC and OM subgroups (Table 1).

The average value of hardness in the Sirona and Orodent groups was 1560.75±147.369 and 1590.70±157.163 VHN, respectively (Table 2).

For the comparison between Sirona and Orodent, the independent sample t-test was applied, where the independent variable in this case was the manufacturer (Sirona and Orodent), while the dependent variable was the hardness (Table 3). A *P*-value of 0.382 indicated no significant difference in hardness between the Sirona and Orodent samples (Table 3).

Table 1.
Sirona and Orodent groups and subgroups.

Group	n	%
Sirona	40	50.0
Orodent	40	50.0
Subgroup	n	%
SC	20	25.0
SM	20	25.0
OC	20	25.0
OM	20	25.0

Table 2.
Sirona and Orodent groups statistics.

Group statistics					
	Group	n	Mean	SD	SEM
Hardness, VHN	Sirona	40	1560.75	147.369	23.301
	Orodent	40	1590.70	157.163	24.850

According to the above data, the mean hardness in SC and SM subgroups was 1595.55±147.790 VHN and 1525.95±142.081 VHN, respectively. Subgroups OC and OM had a mean hardness of 1526.45±149.011 VHN and 1654.95±140.731 VHN, respectively (Table 4). The one-way ANOVA test (Table 5) was applied to compare the four subgroups of the two manufacturers. The *P*-value of 0.016 indicates significant differences between the subgroups of the two companies (Sirona and Orodent). The highest hardness was in the OM subgroup (1654.95±140.731 VHN) compared to the SC subgroup (1595.55±147.790 VHN), OC subgroup (1526.45±149.011 VHN), and SM subgroup (1525.95±142.081 VHN) (*P*=0.016).

Table 4.
Mean hardness in Sirona and Orodent subgroups.

Descriptive statistics								
Hardness								
					95% confidence interval			
	n	Mean	SD	SEM	Lower bound	Upper bound	Minimum	Maximum
SC	20	1595.55	147.790	33.047	1526.38	1664.72	1336	1920
SM	20	1525.95	142.081	31.770	1459.45	1592.45	1267	1755
OC	20	1526.45	149.011	33.320	1456.71	1596.19	1267	1755
OM	20	1654.95	140.731	31.468	1589.09	1720.81	1284	1829
Total	80	1575.73	152.126	17.008	1541.87	1609.58	1267	1920

Table 5.
Comparison between Sirona and Orodent subgroups (one-way ANOVA).

ANOVA					
Hardness					
	Sum of squares	df	Mean square	F	Sig.
Between groups	231504.150	3	77168.050	3.673	0.016
Within groups	1596731.800	76	21009.629		
Total	1828235.950	79			

This analysis compared the two companies and their subgroups to see if there were significant differences between them. In this case, the independent sample t-test was applied, with the company and the subgroups as the independent variables and the hardness value as the dependent variable (Table 6). The results (Table 7) showed no significant differences (*P*=0.137) between the Sirona manufacturer's SC and SM subgroups. The subgroups of the Orodent manufacturer showed statistically significant differences: the OM subgroup had a higher hardness value than the OC subgroup (1654.95±140.731 VHN versus 1526.45±149.011 VHN (*P*=0.008).

Table 3.
Comparison between Sirona and Orodent groups.

Independent samples t-test										
		Levene's test for equality of variances		t-test for equality of means						
		F.	Sig.	t	Df	Sig. (2-tailed)	Mean difference	Std. Error difference	95% confidence interval of the difference	
									Lower	Upper
Hardness	Equal variances assumed	.302	.584	-.879	78	.382	-29.950	34.065	-97.769	37.869
	Equal variances not assumed			-879.	77.67	.382	-29.950	34.065	-97.773	37.873

Table 6.

Independent samples t-test between Sirona/Orodent subgroups.

Descriptive statistics									
Hardness									
						95% confidence interval for mean			
Group	Subgroup	n	Mean	SD	SEM	Lower bound	Upper bound	Mini-mum	Maxi-mum
Sirona	SC	20	1595.55	147.790	33.047	1526.38	1664.72	1336	1920
	SM	20	1525.95	142.081	31.770	1459.45	1592.45	1267	1755
	Total	40	1560.75	147.369	23.301	1513.62	1607.88	1267	1920
Orodent	OC	20	1526.45	149.011	33.320	1456.71	1596.19	1267	1755
	OM	20	1654.95	140.731	31.468	1589.09	1720.81	1284	1829
	Total	40	1590.70	157.163	24.850	1540.44	1640.96	1267	1829

Table 7.

ANOVA test between the Sirona/Orodent subgroups.

ANOVA						
Hardness						
Group		Sum of squares	df	Mean square	F	Sig.
Sirona	Between subgroups	48441.600	1	48441.600	2.305	0.137
	Within groups	798549.900	38	21014.471		
	Total	846991.500	39			
Orodent	Between subgroups	165122.500	1	165122.500	7.861	0.008
	Within groups	798181.900	38	21004.787		
	Total	963304.400	39			

The sample density in the subgroups was measured before the sintering process, and there were no significant differences (Figure 10).

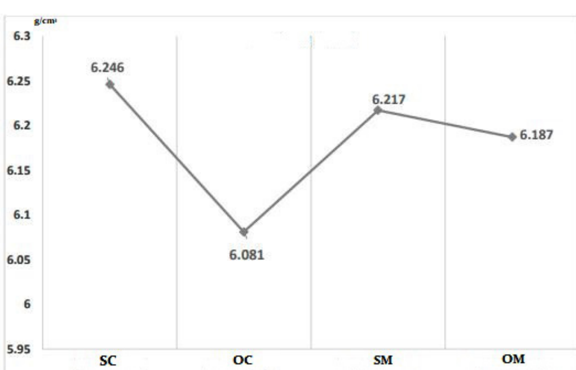

Fig. 10. *Density of all subgroups before the sintering process.*

Discussion

This experimental-comparative research, carried out under in vitro conditions, compared Vickers hardness of two manufacturers, Sirona and Orodent, using two subgroups from each manufacturer (monolithic zirconia and conventional zirconia).

Zirconia is a very homogeneous material that is easy to mill, reducing production delays, machine wear, and surface defects.[14] Some mechanical properties of dental materials (zirconia in the specific case of our work) include roughness, flexural strength, hardness, and wear resistance. Our research focuses on determining two of these properties: VHN and density. The measurement of hardness by the VHN tester, which we used in our scientific experiment, has been found to be one of the values for determining the mechanical properties of zirconia in various dental scientific studies.

In addition to determining the hardness of conventional and monolithic zirconia materials, a comparison was made between the two manufacturers (Sirona and Orodent) and the subgroups of each manufacturer. The difference between monolithic zirconia and conventional zirconia is that monolithic zirconia restorations are exposed to the oral cavity without an additional layer of porcelain veneer. They only need to be stained, polished, and glazed; otherwise, conventional zirconia has a layer of porcelain veneer.[15] Our results show that hypothesis 0 partially holds because a subgroup of the manufacturer Orodent has given a significant difference compared to the results of other subgroups, but in general, there is no difference between the two main groups of manufacturers.

Pre-sintered blocks must be sintered at a higher temperature to achieve sufficient strength after the milling process. During the sintering process, the material shrinks, making the framework denser and stronger.[16] Furthermore, the sintering temperature and duration affect the microstructure of Y-TZP.[17]

Zirconia materials are currently sintered between 1350 ºC and 1600 ºC.[18] If temperatures exceed 1600 ºC, it causes grain growth and increases porosity. Besides, it was observed that the mechanical and optical properties of the zirconia were not sufficient at sintering temperatures of <1400ºC.[19-21] Therefore, in our research, the temperature was 1450 ºC.

In a study by Bruhnke et al.,[12] three monolithic, multi-layered zirconia materials (Katana, Kuraray Noritake, Japan) were selected for comparison: HTML, STML, and UTML. Specimens were sintered in a furnace (Sinterofen Denta-Star P1 plus, Thermo-Star GmbH, Aachen, Germany) according to the manufacturer's instructions with the following parameters: 7 h from room temperature to 1500 °C at 10 °C/min for HTML and to 1550 °C for STML and UTML, a holding time of two hours at firing temperature and cooling to room temperature at 10 °C/min. A different microstructural composition of Katana™ STML, UTML, and HTML accounts for the different mechanical properties. The authors concluded that the range of indications should be considered when selecting the type of monolithic zirconia to fabricate dental restorations since the materials vary greatly in mechanical properties.

A study by Poole et al. [22] compared the physical properties of conventional and monolithic yttria-zirconia materials after low-temperature degradation (LTD) and found slight differences in strength, hardness, and toughness between conventional and monolithic yttria-stabilized zirconia ceramics; however, both materials demonstrate adequate performance for clinical use.

Candido et al.[23] compared conventional zirconia with monolithic zirconia based on various tests. All zirconia tested showed similar VHN, and the monolithic zirconia had roughness similar to conventional zirconia.

Amat et al.[24] investigated the effect of final sintering temperature and grain size on the aging resistance and mechanical properties of zirconia fabricated through colloidal and cold isostatic pressing. Zirconia samples appeared as cylindrical discs. Cyclonic discs were prepared and subjected to five different sintering temperatures ranging from 1400 °C to 1600 °C. The hardness properties of all of the samples sintered at various temperatures did not significantly differ. The sintering temperature of 1500 °C was the most suitable for producing zirconia samples with excellent LTD aging resistance.

Kondo et al.[25] calculated the density of liquid ZrO2 through the aerodynamic levitation technique at temperatures ranging from 2753 K to 3273 K. At its melting point of 2988 K, the density of liquid ZrO_2 was 4.7 g/cm^3 and decreased linearly with increasing temperature.

Sometimes, the glazing materials used to shade and finish ceramic restorations play a role in VHN results. Al-Azzawi et al.[26] found that zirconia coated with GC paste (powder, fluid) has a higher hardness than samples glazed with Ivoclar, VITA group, and Soprano group.

A study by Hashim and Mansoor [27] reported the effect of polishing on the VHN test of monolithic zirconia. The highest VHN was obtained in the group treated with the polishing kit (658.9±66), and the lowest value was shown in the group treated with glaze (538.4±36). The VHN in the group polished with polishing diamond paste was 652.8±66 VHN.

Zirconia exhibits high Vickers hardness around 1300 VHN and complies with criterion F1873 of the American Society for Testing and Materials (ASTM), which suggests values above 1200 VHV.[28,29]

Zirconia crowns undergo an aging process when exposed to some factors from the oral cavity (saliva, blood, water, etc.), which can change their properties.[30,31] Tooth brushing affects the surface of the restorative materials differently. However, according to several studies, abrasive wear during tooth brushing is negligible. [32-34] Candido et al.[34] showed that brushing with distilled or fluoridated toothpaste could not change the roughness and hardness of Y-TZP zirconia after simulating ten years of brushing.

An in vitro study by Shetty et al.[35] compared the effect of different sintering cycles on the surface hardness of full-contour monolithic zirconia. The longest sintering cycle (19 hours) showed the least surface hardness, whereas the short sintering cycle (8 hours) showed the highest surface hardness. In addition, the ultra-short sintering cycle of 2 hours exhibited surface hardness comparable to the other sintering cycles.

Conclusion

The findings highlight the suitability of both zirconia materials from Dentsply Sirona and Orodent manufacturers for dental restorations, with Orodent monolithic zirconia offering potential advantages in terms of hardness.

Competing Interests

The authors declare that they have no competing interests.

References

1. Bona AD, Pecho OE, Alessandretti R. Zirconia as a Dental Biomaterial. Materials (Basel). 2015 Aug 4;8(8):4978-4991. doi: 10.3390/ma8084978. PMID: 28793485; PMCID: PMC5455532.
2. Yang L, Chen B, Meng H, Zhang H, He F, Xie H, Chen C. Bond durability when applying phosphate ester monomer-containing primers vs. self-adhesive resin cements to zirconia: Evaluation after different aging conditions. J Prosthodont Res. 2020 Apr;64(2):193-201. doi: 10.1016/j.jpor.2019.06.008. Epub 2019 Nov 2. PMID: 31690540.
3. Rashid H. The effect of surface roughness on ceramics used in dentistry: A review of literature. Eur J Dent. 2014 Oct;8(4):571-579. doi: 10.4103/1305-7456.143646. PMID: 25512743; PMCID: PMC4253118.
4. Chacun D, Lafon A, Courtois N, Reveron H, Chevalier J, Margossian P, Alves A, Gritsch K, Grosgogeat B. Histologic and histomorphometric evaluation of new zirconia-based ceramic dental implants: A preclinical study in dogs. Dent Mater. 2021 Sep;37(9):1377-1389. doi: 10.1016/j.dental.2021.06.010. Epub 2021 Jul 5. PMID: 34238605.
5. Almohammed SN, Alshorman B, Abu-Naba'a LA. Mechanical properties of five esthetic ceramic materials used for monolithic restorations: A comparative in vitro study. Ceramics.2023;6(2). doi: 10.3390/ceramics6020061.
6. Della Bonna A. Bonding to ceramics: Scientific evidences for clinical dentistry. UK: Scion Publishing, 2009.
7. Nistor L, Grădinaru M, Rîcă R, Mărășescu P, Stan M, Manolea H, Ionescu A, Moraru I. Zirconia Use in Dentistry - Manufacturing and Properties. Curr Health Sci J. 2019 Jan-Mar;45(1):28-35. doi: 10.12865/CHSJ.45.01.03. Epub 2019 Mar 31. PMID: 31297259; PMCID: PMC6592671.
8. Alammar, A., & Blatz, M. B. The resin bond to high-translucent zirconia- Alammar A, Blatz MB. The resin bond to high-translucent zirconia-A systematic review. J Esthet Restor Dent. 2022 Jan;34(1):117-135. doi: 10.1111/jerd.12876. Epub 2022 Jan 24. PMID: 35072329.
9. Kim HK. Optical and Mechanical Properties of Highly Translucent Dental Zirconia. Materials (Basel). 2020 Jul 31;13(15):3395. doi: 10.3390/ma13153395. PMID: 32751942; PMCID: PMC7435650.
10. Lerner H, Nagy K, Pranno N, Zarone F, Admakin O, Mangano F. Trueness and precision of 3D-printed versus milled monolithic zirconia crowns: An in vitro study. J Dent. 2021 Oct;113:103792. doi: 10.1016/j.jdent.2021.103792. Epub 2021 Sep 2. PMID: 34481929.
11. Nakamura K, Harada A, Inagaki R, Kanno T,

Niwano Y, Milleding P, Örtengren U. Fracture resistance of monolithic zirconia molar crowns with reduced thickness. Acta Odontol Scand. 2015;73(8):602-8. doi: 10.3109/00016357.2015.1007479. Epub 2015 Jan 30. PMID: 25635734.
12. Bruhnke M, Awwad Y, Müller WD, Beuer F, Schmidt F. Mechanical Properties of New Generations of Monolithic, Multi-Layered Zirconia. Materials (Basel). 2022 Dec 28;16(1):276. doi: 10.3390/ma16010276. PMID: 36614613; PMCID: PMC9822212.
13. Øilo M, Kvam K, Tibballs JE, Gjerdet NR. Clinically relevant fracture testing of all-ceramic crowns. Dent Mater. 2013 Aug;29(8):815-23. doi: 10.1016/j.dental.2013.04.026. Epub 2013 Jun 6. PMID: 23746750.
14. Ispas A, Iosif L, Murariu-Măgureanu C, Craciun A, Constantiniuc M. Zirconia in dental medicine: A brief overview of its properties and processing techniques. Human and Veterinary Medicine. 2021;13(1):33–39.
15. Caglar I, Ates SM, Yesil Duymus Z. The effect of various polishing systems on surface roughness and phase transformation of monolithic zirconia. J Adv Prosthodont. 2018 Apr;10(2):132-137. doi: 10.4047/jap.2018.10.2.132. Epub 2018 Apr 18. PMID: 29713434; PMCID: PMC5917105.
16. Edwards Rezende CE, Sanches Borges AF, Macedo RM, Rubo JH, Griggs JA. Dimensional changes from the sintering process and fit of Y-TZP copings: Micro-CT analysis. Dent Mater. 2017 Nov;33(11):e405-e413. doi: 10.1016/j.dental.2017.08.191. Epub 2017 Sep 19. PMID: 28939084.
17. Kim MJ, Ahn JS, Kim JH, Kim HY, Kim WC. Effects of the sintering conditions of dental zirconia ceramics on the grain size and translucency. J Adv Prosthodont. 2013 May;5(2):161-6. doi: 10.4047/jap.2013.5.2.161. Epub 2013 May 30. PMID: 23755342; PMCID: PMC3675289.
18. Luthardt RG, Holzhüter M, Sandkuhl O, Herold V, Schnapp JD, Kuhlisch E, Walter M. Reliability and properties of ground Y-TZP-zirconia ceramics. J Dent Res. 2002 Jul;81(7):487-91. doi: 10.1177/154405910208100711. PMID: 12161462..
19. Jang GW, Kım HS, Choe HC, Son MK. Fracture strength and mechanism of dental ceramic crown with zirconia thickness. Procedia Eng. 2011;10:1556–60. doi: 10.1016/j.proeng.2011.04.260.
20. Stawarczyk B, Ozcan M, Hallmann L, Ender A, Mehl A, Hämmerlet CH. The effect of zirconia sintering temperature on flexural strength, grain size, and contrast ratio. Clin Oral Investig. 2013 Jan;17(1):269-74. doi: 10.1007/s00784-012-0692-6. Epub 2012 Feb 23. PMID: 22358379.
21. Öztürk C, Can G. Effect of sintering parameters on the mechanical properties of monolithic zirconia. J Dent Res Dent Clin Dent Prospects. 2019 Fall;13(4):247-252. doi: 10.15171/joddd.2019.038. PMID: 32190207; PMCID: PMC7072090.
22. Poole SF, Rocha Pereira GK, Moris ICM, Marques AG, Ribeiro RF, Gomes EA. Physical properties of conventional and monolithic yttria-zirconia materials after low-temperature degradation. Ceram Int. 2019;45(16):21038–21043. doi: 10.1016/j.ceramint.2019.07.012.
23. Candido LM, Miotto LN, Fais L, Cesar PF, Pinelli L. Mechanical and Surface Properties of Monolithic Zirconia. Oper Dent. 2018 May/Jun;43(3):E119-E128. doi: 10.2341/17-019-L. PMID: 29676981.
24. Amat NF, Muchtar A, Amril MS, Ghazali MJ, Yahaya N. Effect of sintering temperature on the aging resistance and mechanical properties of monolithic zirconia. Journal of Materials Research and Technology; 2019:8(1):1092–1101. doi: 10.1016/j.jmrt.2018.07.017.
25. Kondo T, Muta H, Kurosaki K, Kargl F, Yamaji A, Furuya M, Ohishi Y. Density and viscosity of liquid ZrO_2 measured by aerodynamic levitation technique. Heliyon. 2019 Jul 22;5(7):e02049. doi: 10.1016/j.heliyon.2019.e02049. PMID: 31372532; PMCID: PMC6658727.PMC6658727.
26. Al-Azzawi AKJK, Al Jorani LEA, Fouad RI. Evaluation of the effect of different glazing brands on hardness of monolithic zirconia fabricated by CAD/CAM technique. Tikrit Journal for Dental Sciences. 2023;11(1):57-68
27. Hashim AR, Mansoor N S. Effect of Different Surface Treatments on Surface Roughness and Vickers Micro-Hardness of Feldspathic Porcelain: An In Vitro Study. Mustansiria Dental Journal. 2024;17(1):36–50. doi: 10.32828/mdj.v17i1.1014
28. Vagkopoulou T, Koutayas SO, Koidis P, Strub JR. Zirconia in dentistry: Part 1. Discovering the nature of an upcoming bioceramic. Eur J Esthet Dent. 2009 Summer;4(2):130-51. PMID: 19655651.
29. Roy ME, Whiteside LA, Katerberg BJ, Steiger JA. Phase transformation, roughness, and microhardness of artificially aged yttria- and magnesia-stabilized zirconia femoral heads. J Biomed Mater Res A. 2007 Dec 15;83(4):1096-1102. doi: 10.1002/jbm.a.31438. PMID: 17584902.
30. Kawai Y, Uo M, Wang Y, Kono S, Ohnuki S, Watari F. Phase transformation of zirconia ceramics by hydrothermal degradation. Dent Mater J. 2011;30(3):286-92. doi: 10.4012/dmj.2010-175. Epub 2011 May 20. PMID: 21597215.
31. Catledge SA, Cook M, Vohra YK, Santos EM, McClenny MD, David Moore K. Surface crystalline phases and nanoindentation hardness of explanted zirconia femoral heads. J Mater Sci Mater Med. 2003 Oct;14(10):863-7. doi: 10.1023/a:1025678525474. PMID: 15348523.
32. Ximinis E, Dionysopoulos D, Papadopoulos C, Tournavitis A, Konstantinidis A, Naka O. Effect of tooth brushing simulation on the surface properties of various resin-matrix computer-aided design/computer-aided manufacturing ceramics. J Esthet Restor Dent. 2023 Sep;35(6):937-946. doi: 10.1111/jerd.13043. Epub 2023 Apr 13. PMID: 37052301.
33. Lee JH, Kim SH, Han JS, Yeo IL, Yoon HI. Optical and Surface Properties of Monolithic Zirconia after Simulated Toothbrushing. Materials (Basel). 2019 Apr 10;12(7):1158. doi: 10.3390/ma12071158. PMID: 30974750; PMCID: PMC6480371.
34. Candido L, Fais LM, Pinelli L. Surface roughness and hardness of yttria stabilized zirconia (Y-TZP) after 10 years of simulated brushing. Rev Odontol UNESP. 2014. 43(6):379-383. doi: 10.1590/1807-2577.1049
35. Shetty SK, Varghese FM, Zahid M, Dandekeri S, Feroz F. Effect of Different Sintering Cycles on the Surface Hardness of Full Contour Monolithic Zirconia – An In Vitro Comparative Study. J Evolution Med Dent Sci. 2021;10(28):2089–2093. doi: 10.14260/jemds/2021/427.

***Corresponding author:** *Kujtim Shala, Department of Prosthodontics, University of Prishtina "Hasan Prishtina," Pristina, Republic of Kosovo. E-mail: kujtim.shala@uni-pr.edu*