Research Article

Assessment of the correlation between the tensile and diametrical compression strengths of 3D-printed denture base resin reinforced with ZrO_2 nanoparticles

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Abstract: Background: The mechanical properties of 3D-printed denture base resins are crucial factors for determining the quality and performance of dentures inside a patient's mouth. Tensile strength and diametral compressive strength are two properties that could play significant roles in assessing the suitability of a material. Although they measure different aspects of material behavior, a conceptual link exists between them in terms of overall material strength and resilience. Aim: This study aims to investigate the correlation between tensile strength and diametral compressive strength after incorporating 2% ZrO_2 nanoparticles (NPs) by weight into 3D-printed denture base resin. Methods: A total of 40 specimens (20 dumbbell-shaped and 20 disc-shaped) were produced via 3D printing and divided into two groups (n = 10): (1) 3D-printed denture base resin without NPs and (2) the resin was strengthened with 2% by weight ZrO_2 NPs. Tensile strength and diametral compressive strength were assessed using a universal testing machine. Results: A detrimental relationship was observed between the tensile strength and diametral compressive strength of 3D-printed denture base resin after the addition of NPs. Conclusion: The enhancement of one property does not necessarily mean the enhancement of another. Caution should be taken to not endanger the quality of a material.

Keywords: 3D-printed resin, tensile strength, diametral compressive strength, correlation, ZrO_2 nanoparticles.

Introduction

The interest of researchers in using additive technologies in 3D printing in dentistry has increased significantly. Stansbury and Idacavage in 2016, highlight that there are just a few polymers that are accessible and authorized for intraoral application. According to their chemical makeup, the two primary kinds of classic 3D printing materials are acrylic resins, also known as mono-methacrylate, and di-methacrylate, also known as bis-acryl or composite resins. Light is employed to polymerize these resins (1). These resins use various photoreactive (meth)acrylate monomers to modify material property profiles (2). With regard to applications in 3D printing by vat photopolymerization, low resin viscosity (between 0.1 and 1.3 Pa s.) is a must. It is evident that the composition, polymerization, advantages, and disadvantages differ according to the type of material. Therefore, no one kind can be said to be the best material. Hence, when choosing a material for a particular use, Dental staff should carefully look at the features and benefits of each type of polymer when using computer-aided design to make dentures (3).

To ascertain if 3D-printed materials are suitable for long-term clinical usage in dental restorations, studying their mechanical qualities and biocompatibility is imperative, because materials produced with additive manufacturing (AM) exhibit poor mechanical properties (flexural strength and surface hardness) compared with traditional and milled denture base materials. Comprehensive research into these variables can advance materials science and improve dental patient services (4,5). The amount of polymerization, the inclusion of reinforcing elements, and the printing settings can also have effects on the end product's quality. Consequently, choosing the right dental materials requires careful consideration of these variables to resist chewing stresses (6,7,8).

The use of nanoparticle (NP) fillers is one method that has successfully improved the characteristics of dental resin matrix (9). The ZrO_2 is preferable over other oxides because of its biocompatibility, resemblance to natural teeth, and ability to lessen peri-implant inflammatory reactions. It is a metal oxide with high strength, fracture toughness, and surface hardness (10.,11). In prosthodontics, acrylic resin denture breakage is a persistent major clinical issue; denture fracture causes can be difficult to identify because of a several variables, such as denture function, handling, and processing; denture fractures may be caused by fatigue resulting from repeated masticatory, flexural, and impact loads (12,13,14). Tensile stresses are likely to be the cause of fracture, because they grow perpendicular to a specimen's axis and brittle materials (polymers) are less resistant to tension, which always occurs along the vertical plane of load application and follows the long axis of specimens (15,16).

The diametral compressive strength, elastic modulus, hardness, and fatigue resistance of materials are closely connected. The findings of a diametral compressive strength test can differ even for similar materials; the relationship between filler size and polymeric matrix, and the homogenous distribution of the two variables account for the different results (17).

In a tensile test, measuring the ductility of a material is common. Ductility is an important feature because a material could deform under tensile forces until the fracture moment, and thus, it indicates the workability of a material. Meanwhile, rupture under low tension characterizes fragile materials, which range from susceptible to brittle. In such cases, tensile strength is not indicated when evaluating material reaction because of the low cohesive condition. An alternative method for calculating tensile strength is compressive testing. It is a relatively simple and reproducible test that is defined as the diametral compression test for tension or indirect tension (18). The tensile strength with the diametral compressive strength of a material can provide an idea about overall material ductility, toughness, and permanent deformation when functioning in the oral cavity because it is affected by different stresses. Therefore, to gain an understanding of 3D-printed resin behavior, a correlation assessment between the two load applications before and after the addition of NPs is conducted in the current study (19).

To the best of the authors' knowledge, no previous studies have assessed the correlation between the tensile and diametral compressive strengths of 3D-printed denture base material before or after the addition of NPs.

Although this study was not conducted to optimize the appropriate percentage of ZrO_2 NPs to be included in the polymer matrix of 3D-printed resin to enhance its mechanical properties, it depended on a previous study conducted by the same author who found that 2% of ZrO_2 NPs exerted the most significant effect among other percentages (0%, 2%, and 3%) of ZrO_2 NPs for tensile and diametral compressive tests (20). Accordingly, 2% of ZrO_2 NPs was selected to do the correlation test between tensile and diametral compressive properties.

Consequently, the purpose of this study is to assess the correlation between the tensile strength and diametral compressive strength of 3D-printed denture base resin after the addition of 2% ZrO_2 NPs.

Materials and Methods

A total of 40 specimens were used in this study. For the diametral compressive test, 20 disc-shaped specimens with a thickness of 8 mm (as mentioned by the manufacturer because it is the highest curing depth for 3D-printed samples) and a diameter of 16 mm, (according to Craig`s restorative dental material 2019, the diameter double the thickness of the disc for diametrical compressive test) (21) (Figure 1) were used. For the tensile strength test, 20 dumbbell-shaped specimens with the dimensions provided by ASTM specification D-638M (1986) (19) (Figure 2) were used. For each test, the specimens were divided into two groups (n=10) following with ZrO_2 NP concentration (0% and 2%) by weight.

The selected 3D-printed denture base resin (Optiprint Laviva) was from Dentona Company (Germany). It has a light pink color. Meanwhile, the dental printer used was the DLP open system (Microlay Versus 385). The NPs were from the USA, with 99% purity and size of 40–50 nm (as indicated by the manufacturer).

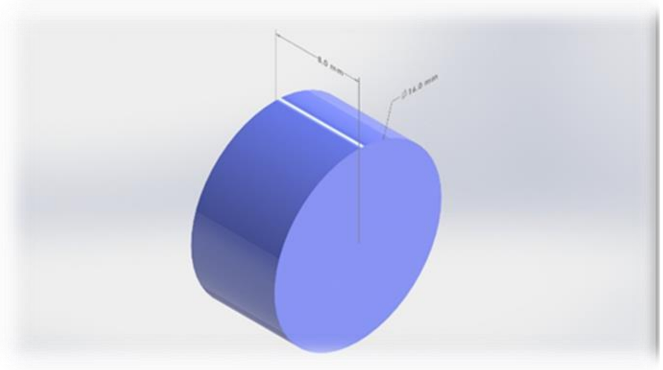

Figure 1: Specimen design for the diametrical compressive strength test.

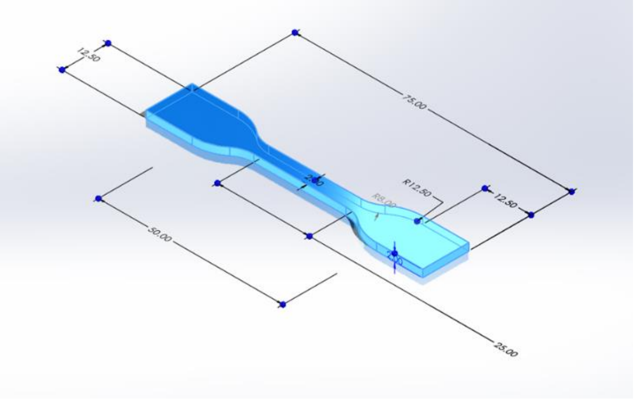

Figure 2: Specimen design for the tensile strength test**.**

The 3D resin was poured into a dark bottle with degradation. A thorough mixing process was performed for the pure resin 1.5 h by using a mechanical mixer at room temperature before adding the NPs. Then, the ZrO_2 NPs were added by 2 wt. % after weighing with a 3 digits electrical scale (DM3, England), mixed well with a magnetic stirrer at 60 °C for 30 min to make the material less viscous (an increase in the viscosity of the material will affect printing quality), and continued stirring at room temperature for 8 h to produce a well-mixed homogenous mixture that is ready for the printing procedure (20). The printing process was started by sending the STL file (software design) of the sample to the printer (DLP VERSUS Microlay, EU).

The software setting of the material was in accordance with the manufacturer's instruction (50 μm layer thickness in (1.61) s/slice in the vertical *Z*-axis). After printing, 99.9% isopropyl alcohol was used to remove extra uncured resin from the specimens. Glycerol painting and placing in an ultraviolet (UV) light polymerization unit for 20 min were performed to complete the polymerization. The supports and base were removed by using a low-speed rotary handpiece. Then, the specimens were immersed for 48 h in distilled water at 37 °C before the testing procedure (20).

Testing procedure

Both tests were performed at the University of Technology, Applied Sciences Department.

Tensile strength test: 'The tensile strength of the specimens was evaluated using a universal testing machine. The ends of a specimen were clamped on two jigs that were spaced apart by a specific value. The specimen was stretched as the two jigs were separated until the specimen was damaged (17).

Tensile strength is calculated using the following equation:

Tensile strength (MPa) = Maximum force (N)/Area (mm^2). Equation (1)

Diametral compressive strength test: Compressive force was applied diametrically to the sample by a computer-controlled electronic universal testing machine until splitting; this compressive force would generate tensile stress in the samples on the plane of force application (Poisson effect) (17).

Diametral compressive stress (σx) is directly proportional to the load (P) applied during compression through the following equation:

$\sigma x = 2P/ \pi DB$. Equation (2)

The maximum vertical tensile stress is located at the center point of the disk specimen, where P is the load, D is the diameter, and B is the thickness of the specimen.

The results were analyzed by using SPSS version 23.0 software.

Results

Descriptive statistics, including mean and standard deviation (SD), for tensile strength were provided with a confidence interval of 95%, as indicated in Table 1. An increase in mean and SD compared with the control was noted after NP addition.

Table 1: Mean values and SD for the tensile strength test.

	N	Mean	SD	95% Confidence Interval for Mean		Minimum	Maximum
				Lower Bound	Upper Bound		
Control	10	14.4513	1.14383	13.6331	15.2695	12.77	16.79
2%	10	24.5021	9.79926	17.4921	31.5121	13.32	36.26

For the diametral compressive strength test, descriptive statistics, including mean and SD, were provided with a confidence interval of 95%, as indicated in Table 2. A decrease in mean and SD compared with the control was noted after adding NPs.

Table 2: Mean values and SD for the diametral compressive strength test.

	N	Mean	SD	Minimum	Maximum
Control	10	17.7750	4.63869	10.91	26.96
2%	10	13.5560	2.36377	11.48	19.16

The box plot in Figure 8 shows an increase in tensile strength after the addition of 2% ZrO_2 NPs, with a decrease in the diametral compressive test after the addition of 2% ZrO_2 NPs.

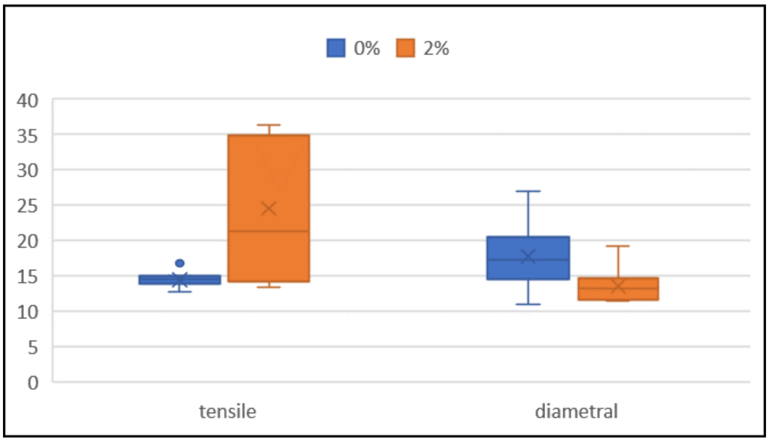

Figure 8: Boxplot that describes the SD and median for the tensile and diametral compressive strength tests before and after the addition of 2% ZrO_2 NPs.

Pearson correlation analysis was employed to explore the associations between tensile strength and diametral compressive strength before and after the addition of 2 wt% ZrO_2 NPs to the 3D-printed denture base resin (Tables 3 and 4).

Table 3: Pearson correlation analysis between tensile strength and diametral compressive strength before the addition of ZrO_2 NPs.

Correlations at 0% ZrO_2 NPs			
		Tensile	Diametral
Tensile	Pearson Correlation	1	0.232
	Sig. (2-tailed)		0.518
	N	10	10
Diametral Compressive	Pearson Correlation	0.232	1
	Sig. (2-tailed)	0.518	
	N	10	10

Table 4: Pearson correlation between tensile strength and diametral compression strength after the addition of 2% ZrO_2 NPs.

Correlations at 2% ZrO_2 NPs			
		Tensile	Diametral
Tensile	Pearson Correlation	1	−0.458
	Sig. (2-tailed)		0.183
	N	10	10
Diametral Compressive	Pearson Correlation	−0.458	1
	Sig. (2-tailed)	0.183	
	N	10	10

The results demonstrate an extremely weak positive correlation between tensile strength and diametral compressive strength before adding NPs.

Meanwhile, it became a weak negative correlation after the addition of 2 wt.% ZrO_2 NPs (Figure 9).

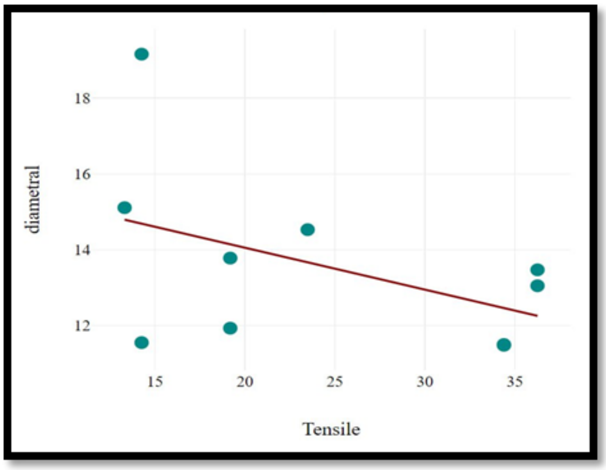

Figure 9: Negative correlation between the tensile and diametral compressive strengths of the 3D-printed denture base resin after the addition of 2 wt.% ZrO_2 NPs.

Discussion

The 3D printing dental industry is expanding increasingly because of its numerous advantages, such as cost-effectiveness, time preservation, and precision with detailed models. Despite these advantages, many drawbacks exist in terms of mechanical properties. Considering every factor is essential when developing dental restorations to withstand forces within the oral cavity during chewing; thus, materials for dental restorations must exhibit exceptional mechanical and physical properties, be easy to handle, and have mild biodegradation rates (22).

Adding nanofillers is one method used to improve the mechanical and physical characteristics of resin-based materials with other materials, such as metals, fibers, and oxides, to generate nanocomposites with improved characteristics. The majority of recent attempts have focused on increasing filler content, and consequently, mechanical characteristics. Meanwhile, certain negative consequences have been documented, including decreased biocompatibility, air gap formation leading to porosity, and agglomeration of NPs that may lead to areas of stress concentration that eventually initiates crack propagation and leads to fracture (23).

Polymers are developed in the manufacture of additive dentistry prostheses. Many factors may affect the behavior of the resin material, including printing orientation, inadequate post-curing time, and fillers that can increase the viscosity of printable resins. These can cause problems, such as clogging, uneven flow, and reduced accuracy in addition to poor printability. In addition, such fillers may settle over time, resulting in increasing thickness with inhomogeneity of the resin, and consequently, poor mechanical properties of printed objects. Resin viscosity must be as low as practically possible to easily apply the monomer coating onto the polymerized layer during printing. To prevent these issues and achieve the best printability and material quality in printable resins, filler type, size, and concentration must be carefully considered (20,24).

The integration of ZrO_2 NPs into the resin matrix enhances characteristics, such as flexural strength and hardness, by forming a more compact and dense structure (9,25). The results of this study revealed a significant increase in tensile strength after the addition of 2 wt.% ZrO_2 NPs, and this finding coincides with previous studies that proved the significant increase in mechanical properties with the addition of ZrO_2 NPs (26,27). The excellent dispersion of the nano-ZrO_2 fillers, which boosts strength because of their nano size and helps internally fill the matrix, may be connected to the improvement in tensile strength (28,29,30).

Conversely, a significant decrease in diametral compressive strength was noted after NP addition. As mentioned earlier, the same materials may exhibit different behavior when tested at varying rates of forces. However, this phenomenon has been attributed to variations in the matrix–filler interaction, filler size, dispersion, interlocking with polymeric molecules, and the connection between them (31,32).

However, given the extremely weak link between polymer chains and the added particles, the particles in their pure form can serve as impurities inside the polymer matrix, and perhaps, lead to the failure of printed parts. Reducing undesirable effects and significantly enhancing mechanical performance may be possible by using NPs with orientated geometries and strong bonding capabilities (34). Fillers typically align via the deposition lines due to the nature of 3D printing; this condition may improve the mechanical, thermal, or electrical conductivity characteristics of the components (34-37). All these factors may directly or indirectly affect material behavior under different load patterns that provide varying results. The addition of ZrO_2 NPs at 2% affects the tensile and diametral compressive strengths of 3D-printed denture base resin, but the effect was different for each. This different behavior of NPs eventual impact on mechanical properties could be useful when choosing the optimum percent of the NPs. to be incorporated within denture base material as it effects tensile strength of the denture base favorably, and this mean the denture become more resistant to deformation under tension. And effect the compression strength unfavorably.

Analysis of correlation in this study start from very weak positive and end to weak negative between tensile strength and diametral compression strength of the 3D printed denture base material after the addition of 2% of the ZrO2 NPs. as many factors may play a role within this change influencing the mechanical behavior of the material. Further investigations needed to point the exact role of NPs.

Conclusion

Overall, the findings of the study contribute to the ongoing exploration of advanced materials for 3D printed dental prostheses, which offers implications for future research and clinical implementation. A negative correlation between tensile strength and diametral compressive strength was noted after the addition of 2 wt.% ZrO_2 NPs to the 3D-printed denture base resin. Enhancing one property does not always imply improving another. To avoid jeopardizing material quality, more researches were needed to determine the optimal percentage of NPs to add to 3D-printed resin to improve its quality.

Conflict of interest

The authors have no conflicts of interest to declare.

Author contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by MIA. The first draft of the manuscript was written by AAF and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Informed consent

Consent to participate For this type of study, formal consent is not required.

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العلاقة بين قوة الشد والضغط القطري لراتنج قاعدة طقم الأسنان المطبوع ثلاثي الأبعاد مع الذرات النانوية لثنائي اوكسيد الزركونيوم.

مروة فريد ابراهيم, عبد الباسط احمدفتح الله, زيد رمزي

المستخلص:

الخلفية: تعد الخواص الميكانيكية لراتنجات قاعدة طقم الأسنان المطبوعة ثلاثية الأبعاد من العوامل الحاسمة في تحديد جودة وأداء أطقم الأسنان داخل فم المريض. قوة الشد وقوة الضغط القطرية هما خاصيتان تلعبان أدوارًا مهمة في تقييم مدى ملاءمة المادة، بينما تقيس قوة الشد وقوة الضغط القطرية جوانب مختلفة من سلوك المادة،الغرض: التحقق من العلاقة بين قوة الشد وقوة الضغط القطرية بعد دمج 2% بالوزن من جزيئات ثنائي اوكسيد الزركونيوم النانوية في راتنج قاعدة طقم الأسنان المطبوع ثلاثي الأبعاد.المواد والطرق: تم إنتاج ما مجموعه 40 عينة, 20 على شكل دمبل و20 على شكل قرص، من خلال الطباعة ثلاثية الأبعاد وتم تقسيمها إلى مجموعتين لكل اختبار، حيث تحتوي كل مجموعة على 10 عيناتو أضافة نسبة 2% وزناً من جزيئات ثنائي اوكسيد الزركونيوم النانوية. تم تقييم قوة الشد وقوة الضغط القطرية باستخدام آلة اختبار عالمية.النتائج: لوحظ وجود علاقة ضارة بين قوة الشد وقوة الضغط القطري لراتنج قاعدة طقم الأسنان المطبوع ثلاثي الأبعاد عند إدخال 2% وزناً من جسيمات ثنائي اوكسيد الزركونيوم النانوية، حيث أدت الى زيادة قوة الشد مع انخفاض قوة الضغط القطري.الاستنتاج: يجب اختيار التركيز المناسب لـ جزيئات ثنائي اوكسيد الزركونيوم النانوية بعناية من أجل تعزيز خصائص الراتنج دون تعريض الخصائص الأخرى للخطرولايعني ذلك أن له تأثيراً إيجابياً على جميع الخواص الأخرى حيث أن العديد من العوامل قد تؤثر على جودة المادة.