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Original Article

A 3D-Simulation Study of the Deformation, Tension, and Stress of 3D-Printed and Conventional Denture Base Materials after Immersion in Artificial Saliva

Mariya Dimitrova[1], Angelina Vlahova[1,3], Raycho Raychev[2], Bozhana Chuchulska[1], Rada Kazakova[1,3]

[1] *Department of Prosthetic Dentistry, Faculty of Dental Medicine, Medical University of Plovdiv, Plovdiv, Bulgaria*
[2] *Department of Mechanics, Faculty of Mechanical Engineering, Technical University of Sofia, Plovdiv Branch, Bulgaria*
[3] *CAD/CAM Center of Dental Medicine, Research Institute, Medical University of Plovdiv, Plovdiv, Bulgaria*

Corresponding author: Mariya Dimitrova, Department of Prosthetic Dentistry, Faculty of Dental Medicine, Medical University of Plovdiv, 3 Hristo Botev Blvd., 4000 Plovdiv, Bulgaria; Email: maria.dimitrova@mu-plovdiv.bg

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Abstract

Introduction: The worldwide application of digital technology has presented dentistry with transformative opportunities. The concept of digital dentures, incorporating computer-aided design (CAD) and computer-aided manufacturing (CAM) techniques, holds the promise of improved precision, customization, and overall patient satisfaction. However, the shift from traditional dentures to their digital counterparts should not be taken lightly, as the intricate interplay between oral physiology, patient comfort, and long-term durability requires thorough examination.

Aim: The aim of the present study was to evaluate and compare the dimensional changes of 3D printed (NextDent, 3D Systems, The Netherlands) and conventional heat-cured (Vertex BasiQ 20, 3D Systems, The Netherlands) denture base resin after immersion in artificial saliva for different periods (7, 14, and 30 days) and then applying 3D simulated deformation, tensional strength, and stress, using the ANSYS software (ANSYS Inc., Pennsylvania, USA).

Materials and methods: For the manufacturing of the test specimens, an STL file was created, using the Free CAD Version 0.19 (Free CAD, Stuttgart, Germany). The dimensions of each specimen were 20 mm in width, 20 mm in length, and 3 mm in thickness. Two hundred experimental bodies were created and divided into two groups (n=100), with half fabricated using a 3D printer (NextDent 5100, NextDent, 3D Systems, The Netherlands) and the other half prepared using the traditional method of heat-curing polymerization in metal flasks. The test samples were then weighed using an analytical balance, immersed in artificial saliva for three periods (7, 14, and 30 days), and reweighed after water absorption. After desiccation at 37°C for 24 hours and then at 23±1°C for 1 hour, the samples were weighed again. Then the data were entered into the specialized program ANSYS and the 3D simulation tests for deformation, tension, and stress were performed. Statistical analysis was performed using the IBM SPSS Statistics Version 0.26 statistical software, which includes descriptive statistics and one-way ANOVA analysis.

Results: The findings weren't statistically significant and indicated that the average metrics for the 3D-printed experimental test samples were marginally greater than those recorded for the conventional samples.

Conclusions: Within the limitations of this study, it is possible to conclude that 3D-printed resin has a lower capacity to withstand deformation, tension, and stress under simulated conditions than conventional dental resin. However, they do not exceed the values accepted by the ISO standard for clinical application of this type of material.

Keywords

3D-printing, 3D simulation, CAD/CAM, denture base material, digital dentures

List of abbreviations	
AS: artificial saliva	**PMMA:** polymethyl methacrylate
CAD/CAM: computer-aided design/computer-aided manufacturing	**STL:** stereolithography, standard triangle language, standard tessellation language
ISO: International Organization of Standardization	**3D:** three dimensional

INTRODUCTION

The increasingly popular CAD/CAM (computer-aided design/computer-aided manufacturing) methods save a lot of effort and provide greater comfort for the patient.[1,2] They are divided into two main groups – additive and subtractive manufacturing.[3] With the subtractive method, the denture base is milled from a pre-polymerized resin block. 3D printing or additive manufacturing (AM) is based on stereolithography (SLA) and encompasses techniques that fabricate objects layer by layer.[4]

Dental resins for removable dentures must be resistant to volume changes under all conditions and not change their dimensions over time. Volumetric changes are expressed in polymerization shrinkage, which is compensated by the significant water sorption of this type of material.[5] This might seriously affect the stability of the denture during chewing and cause the dental resin used to manufacture it to age. Removable dentures are widely preferred by patients who cannot afford more expensive prosthetic restorations, such as implant-supported fixed prostheses.[6] Dentures have been manufactured by different types of acrylics, including the conventional polymer polymethyl methacrylate (PMMA) and the popular nowadays three-dimensional (3D) printed resins. Water sorption and water solubility often occur because these prosthetic restorations are constantly immersed in saliva and always have interactions with oral fluids.[7,8]

Alternating processes of imbibition and drying of acrylics lead to internal stresses and fatigue. As a result, dental resins undergo significant dimensional changes. The water diffuses into the dental resin and inflicts a gradual expansion and volume increase, which may cause aging of the material and discomfort during masticatory function.[9,10] Denture-base resins have low water solubility, which results from the leaching of unreacted monomers and soluble additives into the oral cavity. This is an undesired property and may cause soft tissue reactions.[10,11]

The mechanical characteristics of PMMA resins for the fabrication of partial and complete removable dentures include satisfactory tensile strength (48-62 mPa) and compressive strength (75 mPa).[12,13] Light-curing plastics have lower values than these indicators.[10] Strength qualities are determined depending on several factors, such as the composition of dental resin, degree of polymerization, technology protocol, water sorption, and condition storage. Ideal dental resins should have high impact strength to prevent the risk of breakage when the normal masticatory function is applied. Unmodified acrylics are more fragile, and the addition of plasticizers aims to improve their mechanical qualities.[14,15]

A simulation represents an imitation of a system of a specific type of process over time. Simulations require the use of artificial models that represent the main characteristics of the selected process, and they are usually computer-based.[16] 3D (three-dimensional) simulations involve the application of a 3D computer graphics process, which requires the production of a mathematical network using a specialized program. This product can be presented as a two-dimensional image through rendering or used to digitally simulate a physical phenomenon.[17]

Nowadays, there are various software programs for 3D simulations. The specialized program ANSYS is a software package, whose purpose is to solve practical problems in various engineering fields.[18] It is focused on linear and non-linear equations from solid body mechanics, fluid mechanics, and thermodynamics, as well as issues related to the electromagnetic properties of different materials. The abbreviation ANSYS comes from "ANalysis SYStem" and was founded by Dr. John Swanson, the company developer of ANSYS versions from the first to version 5.1.[19]

AIM

The aim of the current study was to investigate and compare the changes occurring in two types of denture base materials before and after immersion in artificial saliva, subjected to deformation, tension, and stress under 3D-simulated conditions.

MATERIALS AND METHODS

Specimen preparation, design, and manufacturing

Two groups of experimental bodies (n=35) were manufactured using two types of dental resin for removable dentures – 3D-printed resin NextDent (NextDent, 3D Systems, The Netherlands) and PMMA (polymethylmethacrylate) resin Vertex BasiQ 20 (Vertex, 3D Systems, The Netherlands). The test specimens were prepared in rectangular shape with dimensions of 20×20×3 mm, applying two manufacturing methods – conventional heat-curing polymerization and 3D printing. The shape and size of the test sample were designed with Free CAD Version 0.19 and exported as an STL file. The first group of experimental bodies was fabricated using the process of 3D printing, layer by layer, in a specialized NextDent 3D printer (NextDent 5100, 3D Systems, The Netherlands). The second group was prepared using the conventional method of heat-curing polymerization in special metal flasks **(Fig. 1)**.

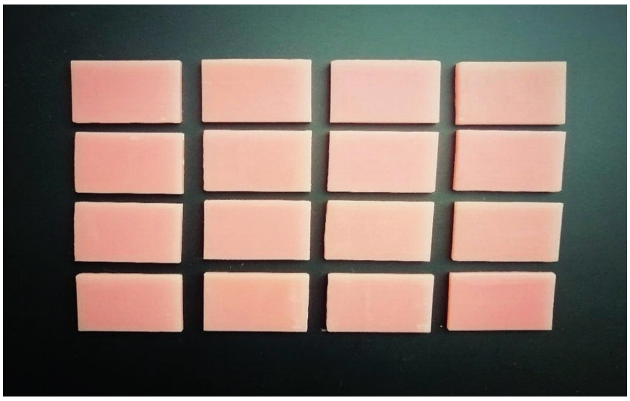

Figure 1. The test specimens before immersion.

Immersion and measurements of the water sorption values of the test specimens

After the specimens were fabricated, their weight was measured and then they were immersed for three periods (7 days, 14 days, and 30 days) in artificial saliva, which was prepared by a chemist in the Department of Chemistry, Medical College of Plovdiv, Medical University of Plovdiv, Bulgaria. After every immersion, the bodies were weighed and dried in the desiccator **(Fig. 2)**. The results of water sorption were documented and statistically processed. The obtained data was imported into the 3D simulation program and then used for the simulation tests, divided into the initial phase and immersion after 1 month.

3D simulation software data import

3D-simulation methods of uniaxial post-deformation loading and bending moment loading were applied to the test specimens, comparing the MPa loading rates of their water sorption for the three time periods. A magnitude force of 700 N was chosen to reproduce the maximum force during normal masticatory function. We compared the results obtained for the two groups of experimental bodies (n=35), with a control group and three immersion periods in artificial saliva (before immersion in artificial saliva – control group, after 7 days, after 14 days, after 1 month). **Fig. 3** shows the direction of application of the load forces on the entire surface of the test body.

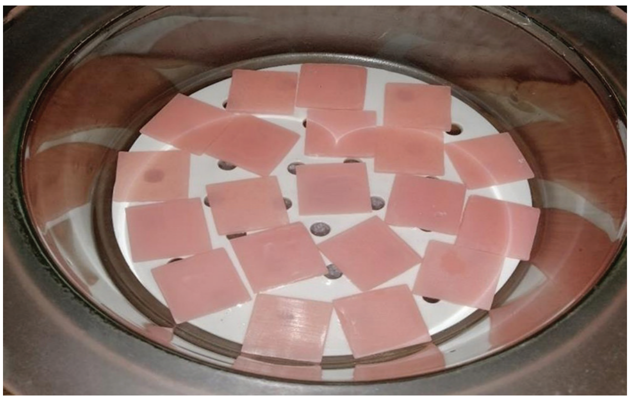

Figure 2. Drying of the test specimens into the desiccator.

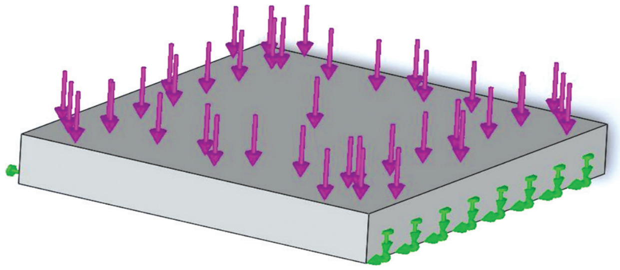

Figure 3. Direction of load forces on the experimental body.

The specialized software program ANSYS (Pennsylvania, USA) allows visualization of the processes through 3D illustrations. The engineering simulation software is designed to enable users to analyze the behavior of test objects when subjected to various physical factors simultaneously.

For our research, the tenth version of the product, ANSYS, Inc. was used, which offers a new Workbench platform. It implements a modern graphical interface and allows us to efficiently manage individual modules and products related to the software. For geometric modeling, the new Design Modeler module, implemented based on the Parasolid core, is built into this platform. The Mechanical simulation module provides the user with the necessary modeling tools. With Workbench, almost the entire ANSYS software suite can be combined with powerful CAD systems, such as SolidWorks, Unigraphics, Inventor, and others, in a single design and calculation environment.

In ANSYS Workbench, the mesh density can be changed. For this purpose, the network density factor (Relevance) can be selected. The Preview Surface Mesh command can be used to preview mesh modifications. In the Statistics section, information about the number of generated nodes and elements can be obtained.

Hypothesis and statistical tests

H_0 – the null hypothesis states that there would be no changes in the tested values of the selected two groups of materials.

H_1 – the alternative hypothesis proposes that there will be a significant change in the investigated values of the tested specimens.

The results obtained from the 3D simulation studies were analyzed and processed using the statistical software package IBM SPSS Statistics Version 0.26, which included descriptive statistics and one-way ANOVA.

RESULTS

Based on the conducted 3D-simulation research on the experimental bodies placed under different conditions: deformation, tension, and stress, respectively for the initial phase after drying, before immersion, and after staying in artificial saliva for 1 month, we performed statistical processing of the data using descriptive analysis and one-way ANOVA analysis **(Table 1, 2)**.

The results of the one-way ANOVA statistical method showed that the standard deviation for Vertex BasiQ 20 was slightly larger but given the upper and lower limits found for the applied strain in both types of materials and the average values, no significant differences were observed. The value for *P* is greater than 0.05, therefore, the differences in deformation at an applied pressure equal to a force equal to 700 N are not significant.

In the one-way ANOVA, as expected, the differences between the two types of materials were not significant **(Table 3, 4)**. The mean voltage and standard deviation values found are almost identical, the difference being minimal. The *p*-value is greater than 0.05, that is, the difference is not

Table 1. Descriptive analysis - deformation of experimental bodies in the initial phase after drying (F=700 N)

Descriptive Analysis								
Deformation test – the initial stage								
	N	Mean value	Standard deviation	Standard error	95% Confidence interval		Min	Max
					Lower border	Upper border		
NextDent	35	1.28023	0.152308	0.025745	1.22791	1.33255	1.035	1.703
Vertex	35	1.24900	0.280732	0.047452	1.15257	1.34543	0.879	2.087
Total	70	1.26461	0.224749	0.026863	1.21102	1.31820	0.879	2.087

Table 2. One-way ANOVA analysis - deformation of experimental bodies in the initial phase after drying

One-way ANOVA					
Deformation test – the initial stage					
	Sum of squares	Degrees of freedom	Sum of the mean value	F	*P*
Between groups	0.017	1	0.017	0.335	0.565
In the groups	3.468	68	0.051	0	0
Total	3.485	69	0	0	0

Table 3. Descriptive analysis - tension in experimental bodies in the initial phase after drying (F = 700 N)

Descriptive analysis								
Tension test – initial stage								
	N	Mean Value	Standard deviation	Standard error	95% Confidence Interval		Min	Max
					Lower border	Upper border		
NextDent	35	195.60229	2.767151	0.467734	194.65174	196.55284	191.230	201.680
Vertex	35	195.34183	3.036428	0.513250	194.29878	196.38488	190.294	200.758
Total	70	195.47206	2.886766	0.345035	194.78373	196.16038	190.294	201.680

Table 4. One-Way ANOVA - tension on experimental bodies in the initial phase

One-way ANOVA					
Tension test – initial stage					
	Sum of squares	Standard deviation	Sum of squared mean	F	*P*
Between groups	1.187	1	1.187	0.141	0.709
In the groups	573.819	68	8.439		
Total	575.006	69			

statistically significant. The deformation of the test body when loaded with a bending moment is represented by the 3D illustration **(Fig. 4)**.

During the stress test in the initial phase, almost equal average values were obtained, establishing a visible but not particularly large difference in the standard of inclination **(Tables 5, 6)**. The lower and upper limits are close in value, and ANOVA analysis confirms that the differences between the two groups of materials are not significant in this case.

In the case of deformation on experimental samples that have been in artificial saliva for 1-month, significant differences in the average values, small differences in the standard deviation, and visibly different upper and lower limits are found according to the type of material **(Tables 7, 8)**.

ANOVA analysis confirmed statistically significant differences in the studied material groups, with the *P*-value being much less than 0.01. **Fig. 5** presents visually a 3D

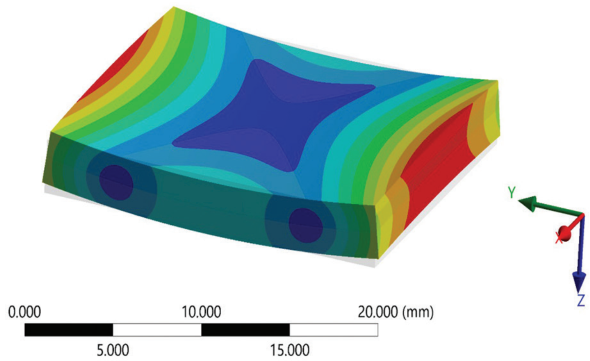

Figure 4. Deformation under load – bending moment.

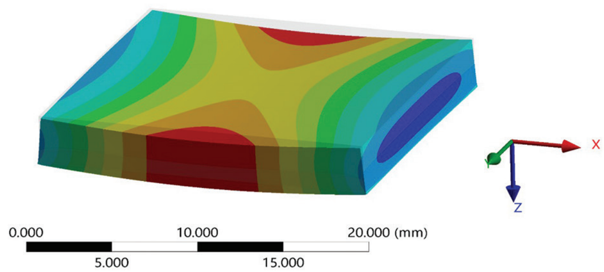

Figure 5. Deformation under uniaxial loading of the experimental body.

Table 5. Descriptive analysis – stress test on experimental bodies in the initial stage after drying (F = 700 N)

Descriptive analysis								
Stress test – initial stage								
	N	Mean Value	Standard deviation	Standard error	95% Confidence interval		Min	Max
					Lower border	Upper border		
NextDent	35	195.60229	2.767151	0.467734	194.65174	196.55284	191.230	201.680
Vertex	35	195.34183	3.036428	0.513250	194.29878	196.38488	190.294	200.758
Total	70	195.47206	2.886766	0.345035	194.78373	196.16038	190.294	201.680

Table 6. One-Way ANOVA - stress on experimental bodies in the initial stage

One-way ANOVA					
Stress test – initial stage					
	Sum of squares	Standard deviation	Sum of squared mean	F	*P*
Between groups	1.156	1	1.197	0.141	0.709
In the groups	533.819	67	8.238	0	0
Total	535.006	68	0	0	0

Table 7. Descriptive analysis - deformation on experimental bodies, after staying in artificial saliva for 1 month (F=700 N)

Descriptive Analysis								
Deformation test – after 1 month								
	N	Mean value	Standard deviation	Standard error	95% Confidence interval		Min	Max
					Lower border	Upper border		
NextDent	35	0.79517	0.101972	0.017236	0.76014	0.83020	0.568	0.987
Vertex	35	0.52346	0.074660	0.012620	0.49781	0.54910	0.401	0.646
Total	70	0.65931	0.163080	0.019492	0.62043	0.69820	0.401	0.987

Table 8. One–way ANOVA – deformation on experimental bodies, after staying for 1 month in artificial saliva

One-way ANOVA					
Deformation test – after 1 month					
	Sum of squares	Degrees of freedom	Square of the mean value	F	*P*
Between groups	1.292	1	1.292	161.778	0.000
In the groups	0.543	68	0.008		
Total	1.835	69			

illustration of the deformation under the uniaxial loading of the experimental body.

Fig. 6 presents the data for the average values, because of the comparative simulation study of the two groups of plastics. There was a significant difference between the means (0.79 for NextDent, 0.52 for Vertex), and there were significant differences in the standard deviation between the two types of materials, as well as in the measured lower and upper limits.

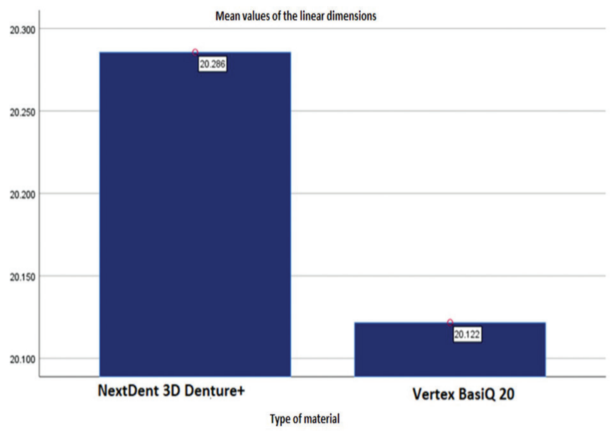

Figure 6. Average values for deformation (in mm) for the type of material.

The means are almost identical, with a slightly larger difference in the standard deviation. The established upper and lower limits are also almost equal **(Tables 9, 10)**. As expected, the one-way ANOVA analysis confirmed that the differences between the two types of plastics were not significant as far as the applied stress was concerned.

Fig. 7 represents a 3D illustration of stress under uniaxial loading of the test body.

The mean and standard deviation have minimal differences, with close lower and upper limits. The *P*-value was

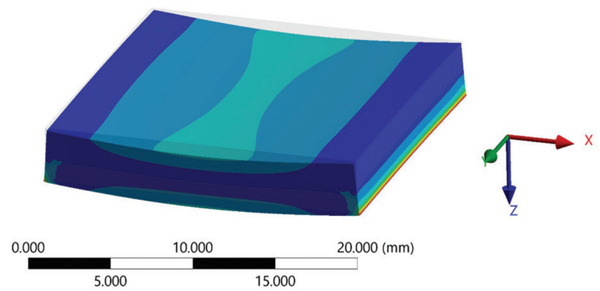

Figure 7. Stress during uniaxial loading of the experimental body.

Table 9. Descriptive analysis - tension on experimental bodies, after a 1-month stay in artificial saliva (F=700 N)

Descriptive Analysis								
Tension test – after 1 month								
	N	Mean value	Standard deviation	Standard error	95% Confidence Interval		Min	Max
					Lower border	Upper border		
NextDent	35	195.15057	2.464755	0.416620	194.30390	195.99724	190.720	199.100
Vertex	35	195.24720	1.716056	0.290066	194.65771	195.83669	192.040	197.813
Total	70	195.19889	2.108777	0.252047	194.69607	195.70171	190.720	199.100

Table 10. One-way ANOVA – tension on experimental bodies, after staying 1 month in artificial saliva

One-way ANOVA					
Tension test – after 1 month					
	Sum of squares	Degrees of freedom	Sum of mean value	F	*P*
Between groups	0.163	1	0.163	0.036	0.850
In the groups	306.675	68	4.510	0	0
Total	306.839	69	0	0	0

greater than 0.05, and ANOVA analysis confirmed that differences between materials were not significant in this case **(Tables 11, 12)**.

As a result of the ANOVA analysis, the following results were obtained – there is a difference between the two types of materials in the case where they were kept for 1 month in artificial saliva and a point pressure was applied to them, with a force equal to 1500 N **(Fig. 8)**.

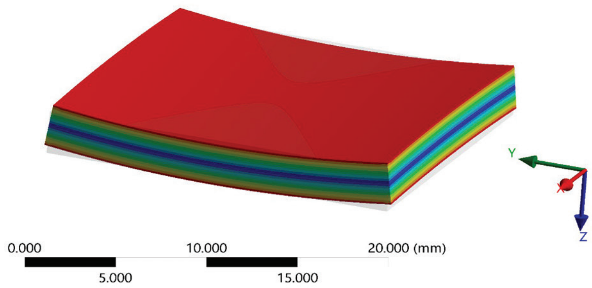

Figure 8. Stress when loading the experimental body - bending moment.

DISCUSSION

The aim of the current study was to evaluate the dimensional changes of two types of denture base materials, immersed in artificial saliva for different periods, after applying 3D simulated tests for deformation, tension, and stress. The results from the conducted experiments support the null hypothesis – there is no statistically significant difference between the tested samples.

The documented nominal values for deformation, tension, and stress not only align with the findings reported in existing literature[4,9,12] but also serve as a foundation for the exploration of innovative avenues in the field. Al-Dwairi et al.[20] illuminate a compelling consideration for practitioners to explore the utilization of plastics in 3D-printed removable dentures, even in the light of their comparatively inferior mechanical properties when compared to PMMA. This underscores the need for a nuanced evaluation that balances material properties with the potential benefits of the 3D printing approach.

Prpić et al.[21] further expand on this perspective by suggesting that the optimization of 3D-printed plastics could be achieved through strategic modifications or reinforcements with nanoparticles. This strategic enhancement, as proposed, holds the promise of unlocking the full potential of the digital method in denture fabrication, emphasizing the importance of continual refinement in materials and methodologies.

Gad et al.[22] shed light on the impact strength dynamics of thermosetting plastic compared to unmodified 3D-printed resin. The observed influence of the layer-by-layer printing process and the specific printing angulation offers valuable insights into the intricacies of the manufacturing process. The parallel loading direction applied in both their study and our stress simulation study further establishes a consistent correlation, adding robustness to the collective body of knowledge.[23,24]

Consistent with the findings of Altarazi et al.[25], the examination of 3D-printed polymers indicates reduced strain levels in contrast to heat-polymerized PMMA. The discussion expands to highlight the multifaceted impact of residual monomer levels and water absorption during the heat cycle on surface hardness and deformation. These nuanced factors emphasize the importance of meticulous material considerations and processing parameters in the pursuit of optimal outcomes.[26-29]

Table 11. Descriptive analysis - stress on experimental bodies after staying for 1 month in artificial saliva

Descriptive analysis								
Stress test – after 1 month								
	N	Mean value	Standard deviation	Standard error	95% Confidence Interval		Min	Max
					Lower	Upper		
NextDent	35	41.0367896	3.98656755	0.67385291	39.6673557	42.4062235	31.71337	48.22439
Vertex	35	29.5999714	3.42393914	0.57875135	28.4238072	30.7761357	23.87100	35.02100
Total	70	35.3183805	6.83973991	0.81750528	33.6875021	36.9492589	23.87100	48.22439

Table 12. One-Way ANOVA - stress on experimental bodies after staying for 1 month in artificial saliva

One-way ANOVA					
Stress test – after 1 month					
	Sum of squares	Degrees of freedom	Sum of mean value	F	*P*
Between groups	2289.014	1	2289.014	165.774	<0.01
In the groups	938.947	68	13.808		
Total	3227.961	69			

The findings in the studies by Aati et al.[30] and Gad et al.[31] contribute valuable insights into the potential enhancements achievable through the incorporation of nanoparticles, specifically ZrO_2NPs and SiO_2NPs, respectively. The role of chemical composition, type, and concentration of nanoparticles, as expounded by Hada et al.'s research[32], further underscores the need for a thorough understanding of these variables in shaping the mechanical properties of 3D-printed materials.

The exploration into the laboratory protocol modifications for polyamide prosthetic base materials[33] introduces a dimension of process refinement. The discovery of a smoother surface resulting from protocol adjustments suggests a ripple effect on various factors and conditions during the fabrication process. These findings align with those of other researchers who have emphasized the influence of different laboratory methods on the surface texture of tested materials[34], emphasizing the intricate interplay between methodologies and material outcomes in dental research.

CONCLUSIONS

A 3D-simulation study was conducted on two groups of test specimens, and subsequent data processing allows us to draw the following conclusions: the 3D deformation simulations revealed that thermosetting acrylics, which had been immersed in artificial saliva for one month, exhibited a slightly higher resistance. The reported values for both types of dental resin meet acceptable standards for their use in the production of removable dentures, affirming the satisfactory mechanical properties of 3D-printed dental resin. In the bending moment stress simulation study, the average values for the experimental 3D-printed test samples were slightly higher than those recorded for the conventional counterparts. However, these values remain within the limits set by ISO standards for the clinical application of this material.

Conflicts of Interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization: M.D.; methodology: M.D., R.R., and A.V.; software: R.R. and A.V.; validation: R.R. and B.C.; formal analysis: R.R. and B.C.; investigation: R.R. and M.D.; resources: M.D. and R.K.; data curation: B.C. and R.K.; writing the original draft preparation: M.D.; writing the review and editing: A.V.; visualization: M.D.; supervision: A.V. and R.R.; project administration: B.C.; funding acquisition: R.K.

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Competing Interests

The authors have declared that no competing interests exist.

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Исследование 3D-моделирования деформации, растяжения и напряжения 3D-печатных и обычных материалов основы зубного протеза после погружения в искусственную слюну

Мария Димитрова[1], Ангелина Влахова[1,3], Райчо Райчев[2], Божана Чучулска[1], Рада Казакова[1,3]

[1] *Кафедра протетической дентальной медицины, Факультет дентальной медицины, Медицинский университет – Пловдив, Пловдив, Болгария*

[2] *Кафедра „Механика", Машиностроительный факультет, Технический университет – София, филиал Пловдив, Болгария*

[3] *Центр CAD/CAM дентальной медицины, Научно-исследовательский институт, Медицинский университет – Пловдив, Пловдив, Болгария*

Адрес для корреспонденция: Мария Димитрова, Кафедра протетической дентальной медицины, Факультет дентальной медицины, Медицинский университет – Пловдив, бул. „Христо Ботев" № 3, 4000 Пловдив, Болгария; E-mail: maria.dimitrova@mu-plovdiv.bg

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Резюме

Введение: Применение цифровых технологий во всём мире открыло в стоматологии преобразующие возможности. Концепция цифровых зубных протезов, включающая методы компьютерного проектирования (CAD) и автоматизированного производства (CAM), обещает повысить точность, индивидуализацию и общую удовлетворённость пациентов. Однако к переходу от традиционных зубных протезов к их цифровым аналогам не следует относиться легкомысленно, поскольку сложное взаимодействие между физиологией полости рта, комфортом пациента и долговечностью требует тщательного изучения.

Цель: Целью настоящего исследования было оценить и сравнить изменения размеров 3D-печатной (NextDent, 3D Systems, Нидерланды) и традиционной термоотверждаемой (Vertex BasiQ 20, 3D Systems, Нидерланды) базисной смолы зубных протезов после погружения в искусственную слюну в течение разных периодов (7, 14 и 30 дней) с последующим применением трёхмерного моделирования деформации, прочности на растяжение и напряжения с использованием программного обеспечения ANSYS (ANSYS Inc., Пенсильвания, США).

Материалы и методы: Для изготовления тестовых образцов был создан файл STL с использованием Free CAD версии 0.19 (Free CAD, Штутгарт, Германия). Размеры каждого образца составляли 20 мм в ширину, 20 мм в длину и 3 мм в толщину. Были созданы двести экспериментальных тел, которые были разделены на две группы (n=100), половина из которых изготовлена с использованием 3D-принтера (NextDent 5100, NextDent, 3D Systems, Нидерланды), а другая половина приготовлена с использованием традиционного метода термоотверждаемой полимеризации. в металлических колбах. Затем тестируемые образцы взвешивали на аналитических весах, погружали в искусственную слюну на три периода (7, 14 и 30 дней) и повторно взвешивали после поглощения воды. После высушивания при 37° C в течение 24 часов, а затем при 23±1° C в течение 1 часа образцы снова взвешивали. Затем данные были введены в специализированную программу ANSYS и проведены 3D-моделированные испытания на деформацию, растяжение и напряжение. Статистический анализ проводился с использованием статистического программного обеспечения IBM SPSS Statistics Version 0.26, которое включает описательную статистику и однофакторный анализ ANOVA.

Результаты: Результаты не были статистически значимыми и показали, что средние показатели экспериментальных тестовых образцов, напечатанных на 3D-принтере, были незначительно выше, чем показатели, зарегистрированные для обычных образцов.

Выводы: В рамках ограничений данного исследования можно заключить, что смола, напечатанная на 3D-принтере, имеет меньшую способность противостоять деформации, растяжению и напряжению в смоделированных условиях, чем обычная стоматологическая смола. Однако они не превышают значений, принятых стандартом ISO для клинического применения этого типа материалов.

Ключевые слова

3D-печать, 3D-моделирование, CAD/CAM, базисный материал протеза, цифровые протезы