The Saudi Dental Journal 36 (2024) 1227–1232

Contents lists available at ScienceDirect

The Saudi Dental Journal

journal homepage: www.ksu.edu.sa
www.sciencedirect.com

In vitro evaluation of the mechanical and optical properties of 3D printed vs CAD/CAM milled denture teeth materials

Mohamed Y. Abdelfattah [a,*], Nouf Al Humayyani [a], Fahad K. Alwthinani [a], Abdulrahman H. Alzahrani [a], Abdulmajeed O. Alotaibi [a], Mohamed Yousef [b], Akram Sayed Ahmed [c], Ahmed Ali [d]

[a] Department of Prosthodontics, Faculty of Dentistry, Taif University, P.O. Box 888, Taif 21974, Saudi Arabia
[b] Department of Prosthodontics, Faculty of Dentistry, Tanta University, P.O. Box 31512, Tanta 31527, Egypt
[c] Department of Dental Biomaterials, Faculty of Dentistry, Tanta University, P.O. Box 31512, Tanta 31527, Egypt
[d] Department of Dental Biomaterials, Faculty of Dentistry, Al-Azhar University, Asuit, Egypt

ARTICLE INFO

Keywords:
Acrylic resin teeth
3D Printing
CAD/CAM
Mechanical properties
Optical properties

ABSTRACT

This laboratory research aimed to assess the Flexural strength, fracture toughness, Volumetric wear and optical properties of various recent 3D-printed denture tooth materials and compare them to CAD/CAM milled materials. Four 3D-printed denture tooth materials (Lucitone Tooth, OnX, Flexcera Ultra +, and VarseoSmile Crown Plus) and one CAD/CAM milled denture teeth material (Ivotion Dent) were used to fabricate fifteen specimens for each material (with total no. of 300 specimens). Tests were conducted according to ISO standards to assess flexural strength, fracture toughness, color staining, and volumetric wear. All materials were printed, washed, cured, or milled following the manufacturer's instructions. Flexural strength and fracture toughness values were obtained by a universal testing machine. Volumetric wear was evaluated using a non-contact optical profilometer. Color stability outcomes were obtained via a spectrophotometer for determining L*a*b* values, with color change (ΔE2000) based on the CIEDE2000 formula. Data were analyzed using one-way ANOVA and Tukey post-hoc analysis ($\alpha = 0.05$). All 3D-printed materials exhibited higher flexural strength values than the milled material ($p < 0.05$). For fracture toughness, two of the 3D-printed materials showed higher values than the milled material, while the other two had lower values. Insignificant variances in volumetric wear were detected between the materials ($p > 0.05$). Color staining results varied, with milled materials generally demonstrating better-staining resistance compared to the 3D-printed materials. 3D-printed denture tooth materials exhibit good mechanical and optical properties, presenting a cost-effective and efficient alternative to CAD/CAM milled materials for denture tooth fabrication.

1. Introduction

Polymethylmethacrylate (PMMA) is a common material used for making acrylic teeth due to its reduced brittleness compared to other materials, better durability, and its ability to form a strong chemical bond with denture bases can enhance overall stability and longevity of the dentures (Anusavice et al., 2012). Despite its advantages, PMMA have some drawbacks, such as polymerization shrinkage, degradation of mechanical properties over time, increased susceptibility to microbial colonization and reduced wear resistance (Powers and Sakaguchi, 2012).

Recently, important enhancements in the chemical structure and technique of manufacturing of PMMA, have been made, including the application of cross-linking agents that permit superior bond between polymer chains, leading to an improved material density, organic and inorganic fillers adding, the coupling agents' modifications and bonding surface enhancement (Grymak et al., 2023).

The advent of digital dentistry has revolutionized the field of prosthodontics, offering new materials and techniques for denture fabrication. The digital prosthetic workflow can be divided into two main groups: the subtractive and the additive. Both techniques have their advantages and applications in digital dentistry, and the choice between

* Corresponding author.
E-mail addresses: m.abdelfattah@tu.edu.sa (M.Y. Abdelfattah), nouf.h@tu.edu.sa (N. Al Humayyani), fwthinani@tu.edu.sa (F.K. Alwthinani), dr.a.alzhrani@tudent.org (A.H. Alzahrani), mjeed@tu.edu.sa (A.O. Alotaibi), mohamed.youssif@dent.tanta.edu.eg (M. Yousef), akram_gad@dent.tanta.edu.eg (A. Sayed Ahmed).

https://doi.org/10.1016/j.sdentj.2024.07.004
Received 16 May 2024; Received in revised form 23 June 2024; Accepted 1 July 2024
Available online 3 July 2024

them often depends on factors such as the type of prosthesis, material requirements, complexity of the design, and the specific needs of the patient (Pham et al., 2021). In milling techniques, pre-polymerized solid blocks are placed in a milling machine where computer-controlled cutting tools carve out the shape of the denture or prosthesis. On the other hand, in the additive manufacturing process, 3D parts are built layer by layer to gradually form the desired shape. Each layer is precisely positioned according to the digital model of the prosthesis, and the layers are bonded together to create the final three-dimensional object Gad et al., 2023. The adoption of additive manufacturing in dentistry represents a transformative shift in manufacturing technology, offering numerous benefits in terms of design flexibility, efficiency, and cost-effectiveness. As the technology continues to evolve, it holds great promise for revolutionizing dental prosthetics and improving patient care. (Mohamed et al., 2023). The use of pre-polymerized resin blanks in subtractive manufacturing helps to ensure the quality and consistency of the denture base, providing a stable foundation for the bonding of denture teeth and ensuring the longevity and comfort of the final prosthesis. They are formulated to release fewer residual monomers, which can be beneficial for patient health by minimizing the risk of allergic reactions or irritation. Gad et al. Gad et al. (2023) Comparing both methods showed that the 3D Printed dentures are more precise and at lesser price than the milled dentures (Alharbi et al., 2016; Alqahtani et al., 2023). The choice between additive and subtractive manufacturing depends on various factors, including the specific requirements of the dental prosthesis, the desired level of accuracy and surface finish, production volume, and budget considerations. Both methods have their strengths and limitations, and dental professionals may opt for one or the other based on their unique needs and preferences.

The adoption of digital dentistry in prosthesis fabrication offers numerous benefits such as improved accuracy as a result of absence of polymerizing shrinkage, enhanced masticatory efficiency and eliminating the need for remounting after processing (Mohamed et al., 2023). So, it is a more time-efficient and cost-effective choice (Tieh et al., 2022).

The introduction of CAD/CAM technology brought significant improvements in the accuracy and reproducibility of denture teeth Srinivasan and Kalberer, 2018. CAD/CAM milled denture teeth are known for their superior mechanical properties and esthetic qualities (Kalberer et al., 2019). However, these advantages come at a higher cost and require specialized equipment and expertise (Dawood et al., 2015).

Recent developments in 3D printing materials specifically designed for denture teeth have shown potential to compete with traditional CAD/CAM milled materials (Digholkar et al., 2016 and Park et al., 2018). 3D printing technology, on the other hand, offers a more flexible and potentially cost-effective alternative Saadi et al., 2023. Materials like Lucitone Tooth, OnX, Flexcera Ultra +, and VarseoSmile Crown Plus have been developed to leverage the benefits of 3D printing, such as reduced material waste, shorter production times, and the ability to customize designs with ease (Osman et al., 2017; Mundhe et al., 2017). Initial studies have indicated that these materials can achieve comparable mechanical properties to their milled counterparts (Tahayeri et al., 2018; Kessler et al., 2020).

Flexural strength and fracture toughness are critical parameters in evaluating the performance of denture teeth (Alqahtani et al., 2023). Flexural strength reflects the maximum stress a material can withstand before breaking, while flexural modulus measures the material's stiffness or resistance to bending, while fracture toughness indicates resistance to crack propagation (Kim et al., 2019). Many investigations have carefully suggested several methods to prevent debonding of teeth from the denture bases. Klaiber et al. reported a considerable improvement of shear bonding strength between custom-prefabricated teeth and CAD/CAM denture bases after monomer application (Mohamed et al., 2023).

Wear resistance is another crucial factor, as denture teeth are subjected to continuous occlusal forces during mastication Gad et al., 2023. The type of abrasive food, parafunctional habit, neuromuscular force, chewing pattern, antagonist materials, and enamel thickness and hardness are some factors that can affect the wear resistance (Pham et al., 2021). Excessive wear can change occlusion and lead to loss of vertical dimensions, reduction of chewing ability, masticatory muscles fatigue, and TMJ Disorders Saadi et al., 2023. Materials with high wear resistance ensure the longevity and functionality of dentures (Grymak et al., 2023).

Digitally-fabricated teeth are more susceptible to color changes from foods and beverages (Dimitrova et al., 2022) as a result of their porous and irregular arrangements. They are monochromatic with limited translucency as they are fabricated as one unit and from one material (Ren et al., 2016). Color changes can disturb the whole esthetic results of a prosthesis, decreasing patient satisfaction and life quality (Villalta et al., 2006, Tieh et al., 2022; Coelho et al., 2024).

Due to the deficient technical information of the performance of 3-D-printed denture teeth, this research intended to study the flexural strength, fracture toughness, wear resistance and color stability of four 3-D printed and one CAD/CAM milled denture teeth resins. The null hypothesis was that there would be no difference between both techniques.

2. Materials and methods

2.1. Sample size calculation

The size of the sample was calculated matching with Cha et al., 2020 (n = 15 /material) with a 95 % confidence interval. A whole of 300 block samples (75 for fracture strength, 75 for fracture Toughness, 75 for wear resistance and 75 for color stability) were required for this study.

2.2. Materials

The materials used in this study are summarized in Table 1.

Table 1
Materials used in this study:

Material Name	Company	Composition	Nature of Material
Lucitone Tooth	Dentsply Sirona, USA	Urethane Methacrylate - Proprietary: 40–50 % [weight] Organic Methacrylate Monomer - Proprietary: 40–50 % [weight] Organic Acrylate Monomer - Proprietary: 1–5 % [weight] Photoinitiator - Proprietary: <1.5 % [weight]	3D-Printed Resin
OnX	Sprintray, USA	Nanoceramic hybrid class II 3D printing resin	3D-Printed Resin
Flexcera Ultra+	Desktop Health, USA	Methyl methylacrylates, methacrylated oligomers and monomers, photo initiators, colorants/dyes, fillers and absorbers.	3D-Printed Resin
VarseoSmile Crown Plus	BEGO, Germany	Esterification products of 4.4′-isopropylidiphenol, ethoxylated and 2-methyl-prop-2enoic acid. Silanized dental glass, methyl benzoylformate, diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide. Total content of inorganic fillers (particle size 0.7 µm) is 30–50 % by mass.	3D-Printed Resin
Ivotion Dent	Ivoclar Vivadent, Liechtenstein	Double-cross linked polymethyl methacrylate	CAD/CAM Milled Resin

2.3. Specimen preparation

Fifteen specimens of each material were fabricated following the manufacturers' instructions. The 3D-printed specimens were printed using a 3D printer (NextDent 5100, 3D Systems Corporation), washed, and post-cured as per the manufacturers' guidelines. The CAD/CAM specimens were milled using a standard milling machine (Yucera Yrc-5X Dry 5 axis Dental Milling Machine, Shenzhen, China) programmed with the manufacturers' specifications [Fig. 1].

2.4. Testing procedures

2.4.1. Flexural strength (ISO 4049:2019)

Rectangular bar-shaped specimens (25 mm × 2 mm × 2 mm) were prepared. The three-point bending test was performed using a universal testing machine (Instron® model 5965, MA) with a crosshead speed of 0.75 mm/min. Fig. 2(a). The flexural strength was calculated using the formula:

$\sigma = 3FL/bd2$

Where F is the load at fracture, L is the support span, b is the specimen width, and d is the specimen thickness Gad et al., 2023.

2.4.2. Fracture toughness (ISO 6872:2015)

Single-edge notched beam (SENB) specimens (25 mm × 5 mm × 2 mm) were prepared with a notch depth of 2.5 mm. Fig. 2 (b). The SENB specimens were tested using a universal testing machine with a crosshead speed of 0.5 mm/min. The fracture toughness was calculated using the formula in the aforementioned standard.

2.4.3. Volumetric wear (ISO 4049:2019)

Specimens were prepared as rectangular blocks (30 mm × 10 mm × 2 mm). Wear tests were conducted using a chewing simulator (CS-4.2, SD Mechatronik) according to methods described by Cha et al., 2020 and Gad et al., 2023 with 120,000 chewing cycles which is equivalent to six months of clinical service (Andreiotelli et al., 2010). A non-contact optical profilometer (Profilm3D, Filmetrics) was used to measure volumetric loss before and after wear testing. The wear volume was calculated by comparing the pre-and post-test profiles of the specimens. The amount of wear in mm. is detected by the loss of specimen height (Witecy et al.,2021).

2.4.4. Color stability (ISO 7491:2000)

Disc-shaped specimens (10 mm diameter × 2 mm thickness) were prepared and polished. The initial color (L*a*b* values) was measured using a spectrophotometer (CM-700d, Konica Minolta) according to the technique described by (Dimitrova et al., 2022). Specimens were immersed in a staining solution (coffee) at 37 °C for 7 days. After immersion, specimens were rinsed, and the final color measurements were taken. The data were recorded using the International Commission of Eclairage (CIE) L * a * b * color system. The L *, a *, and b *values of each tooth before (control) and after immersion The mean values of DL *, Da *, and Db * were automatically calculated via spectrophotometry and recorded. The color change (ΔE2000) was calculated using the previous standard.

2.5. Statistical analysis

All data were analyzed using one-way ANOVA to detect significant differences among the materials, followed by Tukey's post-hoc test for pairwise comparisons. A significance level of $p < 0.05$ was set for all tests. Data analysis was performed using statistical software (SPSS Version 25, IBM Corp).

3. Results

The mean values and standard deviation of the studied mechanical properties were summarized in Table 2.

3.1. Flexural strength (in megapascals (MPa)

The results indicated statistically significant differences in flexural strength among the tested materials ($p < 0.05$). All 3D-printed materials demonstrated higher flexural strength values compared to the CAD/CAM milled material, Ivotion Dent. Specifically, OnX exhibited the highest flexural strength, followed by Flexcera Ultra+, VarseoSmile Crown Plus, and Lucitone Tooth. Ivotion Dent showed the lowest flexural strength among the materials tested.

3.2. Fracture toughness (KIC)

The results mean values with standard deviations showed statistically significant differences among the materials ($p < 0.05$). Lucitone Tooth exhibited the highest fracture toughness, followed by Ivotion Dent, and OnX. Flexcera Ultra + and VarseoSmile Crown Plus showed

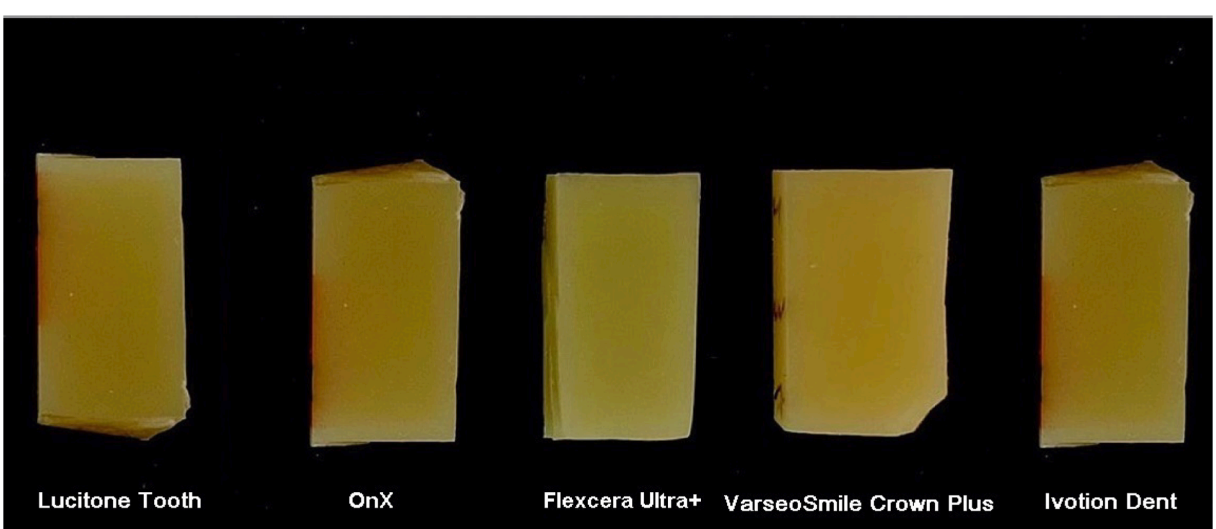

Fig. 1. Specimen preparation process of examples of the prepared specimens.

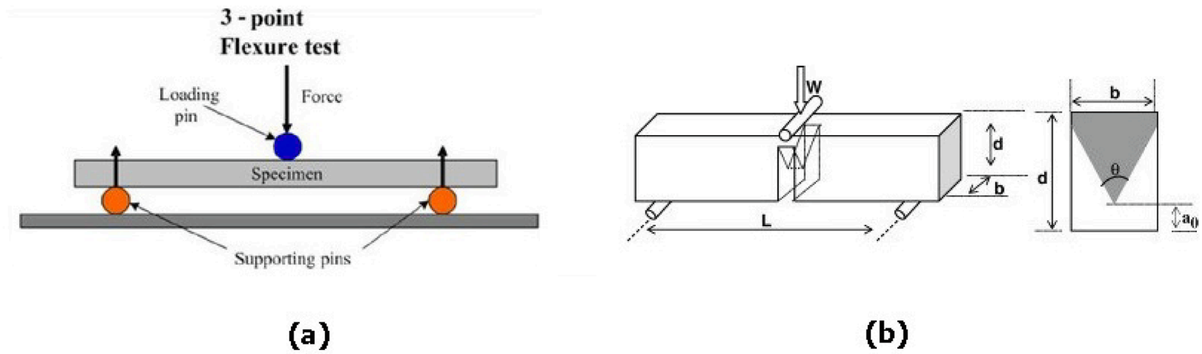

Fig. 2. (a) Three-point flexural strength test. (b) Single-edged-notched-beam test(SENB).

Table 2
Mechanical Properties mean values for all the material specimens.

Materials	Flexural Strength (MPa)	Fracture Toughness (KIc) (Mpa m1/2)	Volumetric Wear (mm^3)
Lucitone Tooth	117.669 ± 4.980b	1.52 ± 0.06a	0.012 ± 0.005a
OnX	97.73 ± 6.026c	1.4 ± 0.28ab	0.023 ± 0.007a
Flexcera Ultra+	135.91 ± 13.534a	0.94 ± 0.06d	0.019 ± 0.012a
VarseoSmile Crown Plus	114.9756 ± 13.92b	0.8 ± 0.07d	0.016 ± 0.019a
Ivotion Dent	83.164 ± 7.123d	1.23 ± 0.16b	0.013 ± 0.003a

*The mean +/- standard deviation of each group is listed in the chart. Groups in each column with different letters are statistically different.

the lowest fracture toughness values.

3.3. *Wear(mm^3)*

The volumetric wear (mm^3), of the 3D-printed denture tooth materials and the CAD/CAM milled denture tooth material. It was evaluated using the University of Alabama (UAB) wear testing machine. The values did not show statistically significant differences among the tested materials ($p > 0.05$), indicating that all 3D-printed materials, as well as the milled material, exhibited comparable wear resistance.

3.4. *Color stability (ΔE2000)*

The color stability, measured as ΔE2000, was evaluated for all materials and the mean values with standard deviations are presented in Table 3. The ΔE2000 results indicated statistically significant differences among the materials ($p < 0.05$). Lucitone Tooth and Ivotion Dent exhibited the lowest color change, indicating superior color stability. OnX and VarseoSmile Crown Plus showed moderate color changes, while Flexcera Ultra + exhibited the highest color change, indicating the least color stability among the tested materials.

Table 3
ΔE2000 mean values for all the material specimens.

Materials	ΔE2000
Lucitone Tooth	0.65 ± 0.24a
OnX	2.04 ± 0.62b
Flexcera Ultra+	3.36 ± 0.76d
VarseoSmile Crown Plus	2.59 ± 0.48b
Ivotion Dent	1.14 ± 0.58a

*The mean +/- standard deviation of each group is listed in the chart. Groups in each column with different letters are statistically different.

4. Discussion

The mechanical and optical properties of denture tooth materials are critical factors in their clinical performance and longevity. This study aimed to compare the flexural strength, fracture toughness, volumetric wear and color stability (ΔE2000) of four recent 3D-printed denture tooth materials against a conventional CAD/CAM milled material. The findings of this study provide insights into the suitability of these materials for use in dental prosthetics (Att et al., 2006; Rosentritt et al., 2004).

The study outcomes exposed significant differences in fracture strength, fracture toughness, wear and color stability between CADD/CAM milled and 3Dprinted teeth; therefore, the null hypothesis was rejected.

All 3D-printed materials exhibited higher flexural strength compared to the CAD/CAM milled material, Ivotion Dent, this was agreed with Chęcińska et al., 2022 and Cha Et Al., 2020. OnX showed the highest flexural strength, followed by Flexcera Ultra+, VarseoSmile Crown Plus, and Lucitone Tooth. The superior flexural strength of OnX and other 3D-printed materials can be attributed to advancements in resin formulations and printing technologies that enhance the polymer matrix's structural integrity. this was in accordance with Alqahtani et al., 2023. High flexural strength is crucial for denture teeth as it indicates the material's ability to withstand masticatory forces without fracturing (Anusavice et al., 2012).

In terms of fracture toughness, Lucitone Tooth demonstrated the highest values, followed by Ivotion Dent and OnX, while Flexcera Ultra + and VarseoSmile Crown Plus had the lowest values. This was in contrast with the conclusions of Ga et al., that described that the CAD/CAD milled resins revealed high fracture strength higher than the 3-D printed resins (Ga et al., 2022). Fracture toughness is a critical parameter that measures a material's resistance to crack propagation, an essential factor for the durability of dental prosthetics [Ferracane, 2001]. The lower fracture toughness of Flexcera Ultra + and VarseoSmile Crown Plus suggests that while these materials may exhibit good initial strength, they might be more susceptible to crack initiation and propagation under stress (Anusavice et al., 2012).

The wear resistance of all tested materials was found to be comparable, with no statistically significant differences observed. This indicates that the wear performance of 3D-printed materials is on par with the CAD/CAM milled material. Wear resistance is a critical factor as it affects the longevity and functionality of denture teeth under masticatory forces. This was against the results obtained from the studies done by Chung et al., and Gad et al. 3D-printed resins usually have weaker interlayer bonding than intralayer bonding (Chung et al.,2018, Gad et al., 2023 and Cha et al., 2022). The absence of glossy enamel layer, that has been reported to have higher wear resistance, in the 3-D printed teeth may explain the decreased wear resistance values in 3D printed teeth (Suwannaroop et al., 2011).

Color stability is paramount for the aesthetic success of denture teeth. The ΔE2000 results revealed that Lucitone Tooth and Ivotion Dent had the lowest color changes, indicating superior color stability. In contrast, Flexcera Ultra + showed the highest color change, suggesting it is more prone to discoloration over time. Color stability in dental materials is influenced by the material's composition and its interaction with staining agents. Materials with higher color stability are preferred as they maintain their aesthetic appearance longer, reducing the need for frequent replacements or adjustments (Dimitrova et al., 2022). All the scanned samples displayed significant coloration after 7 days. This finding agreed with the results of other studies (Hipólito et al., 2013, Ehsani et al., 2022; Paolone et al., 2022). The outcomes revealed that one week exposure to the coffee solution corresponds to approximately 34–67 months of constant intake, which results in color changes Gregorius et al., 2012.

This study has some limitations. The in vitro nature of the tests may not fully replicate the complex oral environment, and long-term clinical studies are needed to validate these findings. Additionally, the study focused on specific 3D-printed and milled materials, and further research could explore a broader range of materials and their performance under various conditions.

5. Conclusions

The study demonstrated that recent 3D-printed denture tooth materials possess good mechanical and optical properties, making them a viable alternative to conventional CAD/CAM milled materials. The high flexural strength and comparable wear resistance of 3D-printed materials are particularly noteworthy. However, considerations regarding fracture toughness and color stability should guide material selection for clinical applications. Continuous advancements in 3D printing technology and material science hold promise for further improving the quality and performance of denture tooth materials.

Ethical statement

The authors emphasize that the follow the guidelines for publishing in the Saudi dental journal.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Alharbi, N., Osman, R.B., Wismeijer, D., 2016. Effects of build direction on the mechanical properties of 3D-printed complete coverage interim dental restorations. J. Prosthet. Dent. 2016 (115), 760–767.

Alqahtani, N.M., Chaturvedi, S., Tomar, S.S., Kumari, L., Gill, S., Nayan, K., Shariff, M., Bhagat, T.V., Addas, M.K., Chaturvedi, M., 2023. Fracture toughness of 3D printed denture teeth. Technol. Health Care. 31(1):247-258. doi: 10.3233/THC-220288. PMID: 36031920.

Andreiotelli, M., Att, W., Strub, J.R., 2010. 2010 Prosthodontic complications with implant overdentures: a systematic literature review. Int. J. Prosthodont 23, 195–203.

Anusavice, K.J., Shen, C., Rawls, H.R., 2012. Phillips' science of dental materials. Elsevier. Health Sci. 54–59.

Att, W., Komine, F., Gerds, T., Strub, J.R., 2006. Fracture resistance of single-tooth implant-supported all- ceramic restorations: an in vitro study. J. Prosthet. Dent. 95 (2):111-116.

Cha, H.S., Park, J.M., Kim, T.H., et al., 2020. Wear resistance of 3D-printed denture tooth resin opposing zirconia and metal antagonists. J. Prosthet. Dent 2020 (124), 387–394.

Chęcińska, K., Chęciński, M., Sikora, M., Nowak, Z., Karwan, S., Chlubek, D., 2022. The Effect of Zirconium Dioxide (ZrO2) Nanoparticles Addition on the Mechanical Parameters of Polymethyl Methacrylate (PMMA): A Systematic Review and Meta-Analysis of Experimental Studies. Polymers (Basel). 14(5):1047. doi: 10.3390/polym14051047. PMID: 35267870; PMCID: PMC8914807.

Chung, Y.J., Park, J.M., Kim, T.H., et al., 2018. 3D printing of resin material for denture artificial teeth: chipping and indirect tensile fracture resistance. Materials (Basel) 11, 1798.

Coelho, S.R.G., da Silva, M.D.D., Nunes, T.S.B.S., Viotto, H.E.C., Marin, D.O.M., Pero, A. C., 2024. Effect of immersion in disinfectants on the color stability of denture base resins and artificial teeth obtained by 3D printing. J. Prosthodont. 33(2):157-163. doi: 10.1111/jopr.13663. Epub 2023 Feb 24. PMID: 36740784.

Dawood, A., Marti Marti, B., Sauret-Jackson, V., Darwood, A., 2015. 3D printing in dentistry. Br. Dent. J. 2015 (219), 521–529.

Dimitrova, M., Chuchulska, B., Zlatev, S., Kazakova, R., 2022. Colour Stability of 3D-Printed and Prefabricated Denture Teeth after Immersion in Different Colouring Agents-An In Vitro Study. Polymers (Basel).;14(15):3125. doi: 10.3390/polym14153125. PMID: 35956640; PMCID: PMC9371044.

Ehsani, M., Sadighpour, L., Geramipanah, F., Ehsani, A., Shahabi, S., 2022. Color stability of different denture teeth following immersion in staining solutions. Front. Dent 2022 (19), 11–13.

Ferracane, J.L. 2001 Materials in Dentistry: Principles and Applications. Lippincott Williams & Wilkins.

Gad, M.M., Alghamdi, R., Al-Ghamdi, R., Al-Jefri, A., Akhtar, S., Khan, S.Q., Alalawi, H., Al-Qarni, F.D., 2023. Wear and Fracture Resistance of 3D-Printed Denture Teeth: An In Vitro Comparative Study. J. Prosthodont. 32(2):170-177. doi: 10.1111/jopr.13521. Epub 2022 Apr 27. PMID: 35411606.

Gregorius, W.C., Kattadiyil, M.T., Goodacre, C.J., Roggenkamp, C.L., Powers, J.M., Paravina, R.D., 2012. Effects of ageing and staining on color of acrylic resin denture teeth. J. Dent. 2012, 40, e47 e54.

Grymak, A., Tieh, M.T., Yang, A.H.X., Choi, J.J.E., 2023 Aug. Development of predictive algorithms for the wear resistance of denture teeth materials 2023. J. Mech. Behav. Biomed. Mater. 144, 105984 https://doi.org/10.1016/j.jmbbm.2023.105984. Epub 2023 Jun 25 PMID: 37392604.

Hipólito, A.C., Barao, V.A.R., Faverani, L.P., Ferreira, M.B., Assunção, W.G., 2013. Color degradation of acrylic resin denture teeth as a function of liquid diet: Ultraviolet-visible reflection analysis. J. Biomed. Opt. 2013 (18), 105005.

ISO 4049:2019. 2019. Dentistry—Polymer-based restorative materials. International Organization for Standardization.

Kalberer, N., Mehl, A., Schimmel, M., Müller, F., 2019. CAD-CAM dentures: The digital era of complete dentures? A case report of an esthetic, functional, and efficient protocol. Int. J. Prosthodont. 32, 182–185.

Kessler, A., Hickel, R., Reymus, M., 2020. 3D printing in dentistry-state of the art. Oper. Dent. 2020 (45), 30–40.

Kim, S.Y., Shin, Y., Lee, J.H., Shin, S.W., Jun, S.H., 2019. Comparison of the fracture resistance of interim denture polymer according to the fabrication method. J. Adv. Prosthodont. 2019 (11), 55–64.

Mohamed, A., Takaichi, A., Kajima, Y., Takahashi, H., Wakabayashi, N., 2023. Physical Properties of Additively Manufactured Tooth-Colored Material Attached to Denture Base-Colored Material in a Printed Monolithic Unit. Polymers (Basel). 15(9):2134. doi: 10.3390/polym15092134. PMID: 37177280; PMCID: PMC10181472.

Mundhe, K., Jain, V., Pruthi, G., Shah, N., 2017. Clinical study to evaluate and compare the wear resistance of three different types of denture teeth materials. J. Indian. Prosthodont. Soc. 2017 (17), 240–247.

Osman, R.B., Alharbi, N., Wismeijer, D., 2017. Build angle: Does it influence the flexural strength of 3D- printed interim prosthetic materials? Int. J. Prosthodont. 2017 (30), 182–184.

Paolone, G., Formiga, S., De Palma, F., Abbruzzese, L., Chirico, L., Scolavino, S., Goracci, C., Cantatore, G., Vichi, 2022 A. Color stability of resin-based composites: Staining procedures with liquids. A narrative review. J. Esthet. Restor. Dent., 37, 8–11.

Park, J.Y., Bae, S.Y., Lee, J.H., Kim, J.H., Kim, W.C., 2018. Evaluation of additive manufacturing and milling processes of CAD/CAM fabricated denture teeth. J. Prosthodont. Res. 2018 (62), 56–63.

Pham, D.M., Gonzalez, M.D., Ontiveros, J.C., Kasper, F.K., Frey, G.N., Belles, D.M., 2021. Wear resistance of 3D Printed and prefabricated denture teeth opposing zirconia. J. Prosthodont. 30(9):804- 810. doi: 10.1111/jopr.13339. Epub 2021 Feb 11. PMID: 33486808.

Powers, J.M., Sakaguchi, R.L., 2012. Craig's restorative dental materials. Elsevier Health. Sci. 41, 128.

Ren, J., Lin, H., Huang, L., Wu, Y., Hao, Y., 2016. Comparison of the translucency and color stability of monolithic and bilayer dental ceramics. J. Prosthet. Dent. 2016 (116), 898–904.

Rosentritt, M., Behr, M., Handel, G., Kolbeck, C., Schneider-Feyrer, S., In vitro fracture resistance of metallic and tooth-colored posts and cores. J. Oral Rehabil. 31(7):659-664.

Saadi, A.S.A., El-Damanhoury, H.M., Khalifa, N. 2023. 2D and 3D Wear Analysis of 3D Printed and Prefabricated Artificial Teeth. Int. Dent. J., 73(1):87-92. doi: 10.1016/j.identj.2022.10.002. Epub 2022 Nov 11. PMID: 36372591; PMCID: PMC9875236.

Srinivasan, M., Kalberer, N., 2018. CAD/CAM milled versus rapidly prototyped (3D printed) complete dentures: an in vitro evaluation of trueness. J. Prosthodont. Res. 2018 (62), 274–280.

Suwannaroop, P., Chaijareenont, P., Koottathape, N., et al., 2011. In vitro wear resistance, hardness and elastic modulus of artificial denture teeth. Dent. Mater. J 2011 (30), 461–468.

Tahayeri, A., Morgan, M.C., Fugolin, A.P., Bompolaki, D., Athirasala, A., Pfeifer, C., et al., 2018. 3D printed versus conventionally cured provisional crown and bridge dental materials. Dent. Mater. 2018 (34), 192–200.

Tieh, M.T., Waddell, J.N., Choi, J.J.E., 2022. Optical and mechanical properties of conventional, milled and 3D-printed denture teeth. J. Mech. Behav. Biomed. Mater.

126:105061. doi: 10.1016/j.jmbbm.2021.105061. Epub 2021 Dec 22. PMID: 34963102.
Villalta, P., Lu, H., Okte, Z., Garcia-Godoy, F., Powers, J.M., 2006. Effects of staining and bleaching on color change of dental composite resins. J. Prosthet. Dent. (95), 137–142.
Witecy, C., Ganss, C., Wöstmann, B., et al., 2021. Monitoring of erosive tooth wear with intraoral scanners in vitro. Caries Res. 2021 (55), 215–224.