RESEARCH ARTICLE

OPEN ACCESS

Effect of Water Sorption on the Mechanical Properties of Surgical Splint Materials: 3D-printed *vs* Conventional Resin

Yuko Matsuki[1,#], Enrique Ezra Zuñiga Heredia[2,#], Yuka Egami[2], Kana Egami[2] and Masahiro Iijima[2,*]

[1]*Division of Advanced Clinical Education, Department of Integrated Dental Education, School of Dentistry, Health Sciences University of Hokkaido, Hokkaido, Japan*
[2]*Division of Orthodontics and Dentofacial Orthopedics, Department of Oral Growth and Development, School of Dentistry, Health Sciences University of Hokkaido, Hokkaido, Japan*

Abstract:

Introduction: Recently, digital technologies have become common in clinical dental practice, which may provide benefits to clinicians and patients. This study investigated how water absorption affected the mechanical properties of three-dimensionally (3D)-printed surgical splint materials used to position bones during orthognathic surgery.

Methods: Two 3D-printing materials, Dental LT Clear (Formlabs) and Splint (SprintRay), as well as a conventional acrylic resin (Unifast III, GC), were purchased for this study. We prepared wire (2 × 2 × 25 mm) and disc-shaped (14 mm diameter and 2 mm in thickness) specimens *via* 3D-printing or pouring into silicon molds. All materials were subjected to the ISO 4049 three-point bending test, and the water absorptions of samples immersed in artificial saliva for 28 days were calculated as per ISO 10477. Changes in mechanical properties (hardness, and the modulus of elasticity) were evaluated *via* nanoindentation testing. Chemical parameters were determined using Fourier-Transform Infrared Spectroscopy (FTIR). The data were compared using ANOVA and the Tukey multiple comparisons test.

Results: The bending strengths and elongations of both 3D-printed materials were significantly greater than those of conventional acrylic resin. The FTIR data indicated that the water absorptions of both 3D-printed materials were significantly greater than those of conventional PMMA (polymethyl methacrylate)-based resin. The hardness and elastic modulus values of both 3D-printed materials (obtained using the nanoindentation test) decreased significantly as the immersion period rose; those of the conventional acrylic resin did not.

Discussion: The improved mechanical properties of 3D printed materials would demonstrate greater resistance to the stresses imparted by the muscles associated with functional mandibular movement, while also reducing the risk of splint chipping during intermaxillary fixation. On the other hand, there is concern that the stability of the mechanical properties of 3D printed materials may be compromised by water absorption in moisture-rich environments.

Conclusion: Although 3D-printed materials exhibit superior mechanical properties, their water absorption and extent of degradation on immersion in artificial saliva were higher than those of a conventional PMMA-based resin.

Keywords: 3D printing, Surgical splint, Water sorption, Mechanical properties, Nanoindentation test.

*Address correspondence to this author at the Division of Orthodontics and Dentofacial Orthopedics, Department of Oral Growth and Development, School of Dentistry, Health Sciences University of Hokkaido, Hokkaido, Japan. Tel: +81-133-23-2975; E-mail: iijima@hoku-iryo-u.ac.jp
#These authors contributed equally to this work.

1. INTRODUCTION

Recently, digital intraoral scanning and cone-beam computed tomography have become common in clinical dental practice [1-3]. Three-dimensional (3D) computer-assisted simulation of orthognathic surgery that corrects jaw deformities is more accurate than conventional two-dimensional cephalometric prediction and the use of surgical models; human error is minimized [4, 5].

Surgical splints precisely position the maxilla and mandible during orthognathic surgery. Computer-aided design /computer-aided manufacturing (CAD/CAM) yield digitally designed, 3D-printed surgical splints; the accuracy of which is high [5, 6]. Traditional acrylic resin splints, hand-fabricated using stone dental models, are less accurate [7-10].

After orthognathic surgery, surgical splints (final splint) usually remain in place for 1 week to 1 month; the splints must be dimensionally and chemically stable, because they may certainly affect the precision of the occlusal positioning. Both polymethyl methacrylate (PMMA; conventional acrylic resin) and the resins used for 3D printing absorb water [11]. This may compromise splint durability *via* degradation of the mechanical properties.

The purpose of this study was to explore water-mediated degradation of both 3D-printing materials and conventional acrylic resin. This is the first study that reports the water absorption characteristics of 3D-printed materials for surgical splint.

2. MATERIALS AND METHODS

2.1. Materials and Sample Preparation

Two commercial 3D-printing materials, Dental LT Clear (Formlabs, Somerville, MA, USA) and Splint (SprintRay, Los Angeles, CA, USA), and an autopolymerizing PMMA-based resin (Unifast III, GC, Tokyo, Japan) were purchased (Table 1). CAD software (Tinkercad, Autodesk, San Rafael, CA, USA) was used to design rectangular wires of cross-section 2 × 2 mm and length 25 mm, and discs 14 mm in diameter and 2 mm in thickness that were 3D-printed by a digital light processing (DLP) device (Pro 95, SprintRay). The layer thickness was 50 μm and the X/Y resolution was 95 μm. Following the manufacturer's recommendations, the specimens were initially washed with 99% (v/v) isopropyl alcohol, subjected to multistage automated washing, and dried (Pro Wash/Dry, SpringRay). Post-processing employed a post-curing device (Pro Cure, SpringRay) and proceeded at 30°C for 15 min under a 405-nm light-emitting diode array. The comparative specimens were prepared *via* thorough mixing of appropriate amounts of the PMMA polymer and MMA (methyl methacrylate) monomer liquid, and this PMMA-based resin mixture was poured into silicon molds.

2.2. Three-point Bending Test

The three-point bending test (n = 10) employed a span size of 12 mm (ISO specification 4049, 2019). Specimens were loaded onto a universal testing machine (EZ Test, Shimadzu, Kyoto, Japan) with a 20-N load cell and subjected to a deflection of at least 4 mm at 1 mm/min, or until

fracture. The elastic modulus and the bending strength (the force at bending failure) were calculated using inbuilt software (Trapezium ver. 2, Shimadzu).

Table 1. Materials used in the present study.

No.	Abbreviations	Main Component	Product Name	Manufacturer
1	DLC	Methacrylic oligomer	Dental LT Clear	FormLabs
2	SP	Acrylic Oligomers	Splint	SprintRay
3	UF	Polymethyl methacrylate	Uni Fast III	GC

Note: This table summarizes the abbreviations, chemical compositions, product names, and manufacturers of the three materials investigated in this study. The descriptions provided are as proportioned by the manufacturers.

2.3. Water Absorption

All specimens (n = 10/group) were dried in a desiccator containing silica gel (Middle Granule, Kanto Chemical Co. Inc., Tokyo, Japan) for 24 h at 37 ± 1°C, and then in a second desiccator at 23 ± 1°C for 2 h, and weighed using an analytical balance (HR-200, A&D Company, Tokyo, Japan) with an accuracy of 0.1 mg. This cycle was repeated for approximately 3 weeks, at which time constant mass (M_1) was obtained. All specimens were then immersed in individual 10-mL plastic vials containing artificial saliva with $CaCl_2$ and NaH_2PO_4 with a Ca/PO_4 for 30 days at 37ºC, then the surface liquid was wiped off using a dry cloth, and weighed (M_2). Water sorption (Ws), representing the percentage increase in weight, was calculated using the following formula:

$$Ws = \left(\frac{M_2 - M_1}{M_1} \right) \times 100\%$$

2.4. Characterization of Chemical Structure by Fourier-transform Infrared Spectroscopy (FTIR)

Chemical parameters were investigated *via* FTIR in the attenuated total reflection (ATR) mode using a diamond detector (FT/IR-6600, Jasco, Tokyo, Japan). Spectra were collected from 4,000 to 400 cm⁻¹ at a resolution of 4 cm⁻¹. The spectrum number averaged 32; this ensured a high signal-to-noise ratio. After baseline correction, the spectra were normalized to facilitate comparisons.

2.5. Degradation of Mechanical Properties as Revealed by the Nanoindentation Test

During immersion as described above, all specimens underwent nanoindentation testing on days 0, 1, 3, 7, 14, and 30 to evaluate mechanical properties such as hardness and the elastic modulus (ENT-1100a instrument, Elionix, Tokyo, Japan). A Berkovich-type diamond indenter (a triangular pyramid with a ridge line angle of 115°) was used for the measurements. To investigate the mechanical properties of both the surface and the deep layers, two indentation loads were applied: 10 mN (indentation depth approximately 1,500 nm) and 100 mN (indentation depth

approximately 5,000 nm). Ten samples of each material were tested at each of 10 sites. The hardness and elastic modulus were calculated using the inbuilt software that met the ISO 14577-1 guidelines.

2.6. Statistical Analysis

All statistical analyses employed SPSS version 22 (IBM, Armonk, NY, USA). Data normality was assessed using the Shapiro-Wilk test and by drawing Q-Q plots. The Levene test was employed to evaluate the variance homogeneity across the groups. After confirming these assumptions, one-way analysis of variance (ANOVA) was used to compare the mean values across groups, and the Tukey post-hoc test was employed for pairwise comparisons when significant differences were apparent. The level of significance was set to $p < 0.05$ for all tests.

Power analysis employed G*Power ver. 3.1 with an assumed effect size (f) of 0.4 as suggested by the literature [12-14], an alpha level of 0.05, and a power of 0.80. The analysis included three groups and six repeated

measurements; the non-sphericity correction was 0.2 and the correlation among repeated measures was 0.5. The required sample size was 30; the actual power was 0.827.

3. RESULTS

The three-point bending curves in Fig. (**1**) show that the elastic modulus, bending strength, and elongation (deflection to fracture) of both 3D-printing materials were similar, and significantly greater than those of conventional PMMA-based resin. On immersion in artificial saliva, the water absorptions of both 3D-printing materials increased significantly over time, as shown in Fig. (**2**), and were significantly greater than those of conventional PMMA-based resin. On FTIR, both 3D-printed materials exhibited an increase in the water peak intensity at 3,600 cm^{-1}, as shown in Fig. (**3**). The hardness and elastic modulus values of the nanoindentation test decreased significantly with increasing duration of immersion as shown in Fig. (**4**). The conventional PMMA-based resin exhibited no significant degradation of mechanical properties on immersion.
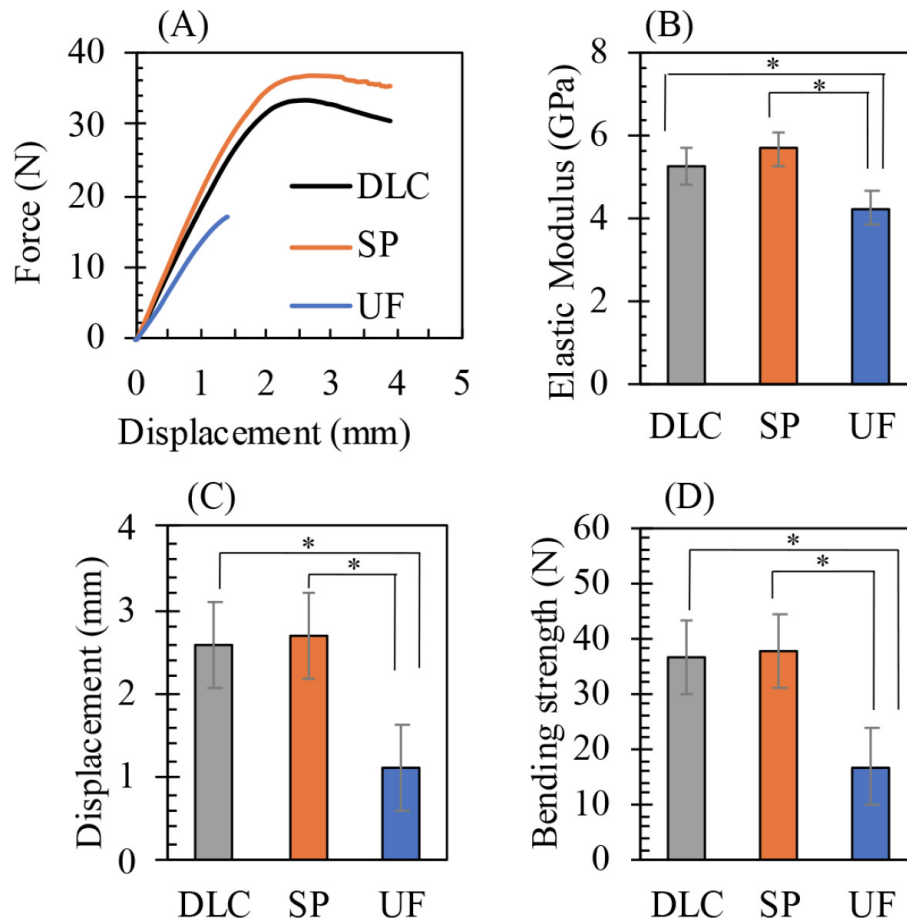

Fig. (1). Representative mechanical results of the three-point bending test, including: (**A**) force–displacement curves (y-axis: force in newtons [N]; x-axis: displacement in millimeters [mm]), (**B**) elastic modulus values (y-axis: GPa), (**C**) maximum displacement before failure (y-axis: mm), and (**D**) bending strength (y-axis: N). DLC: Dental LT Clear; SP: Splint; UF: Uni Fast III. *$p < 0.05$ indicates statistically significant differences among groups.
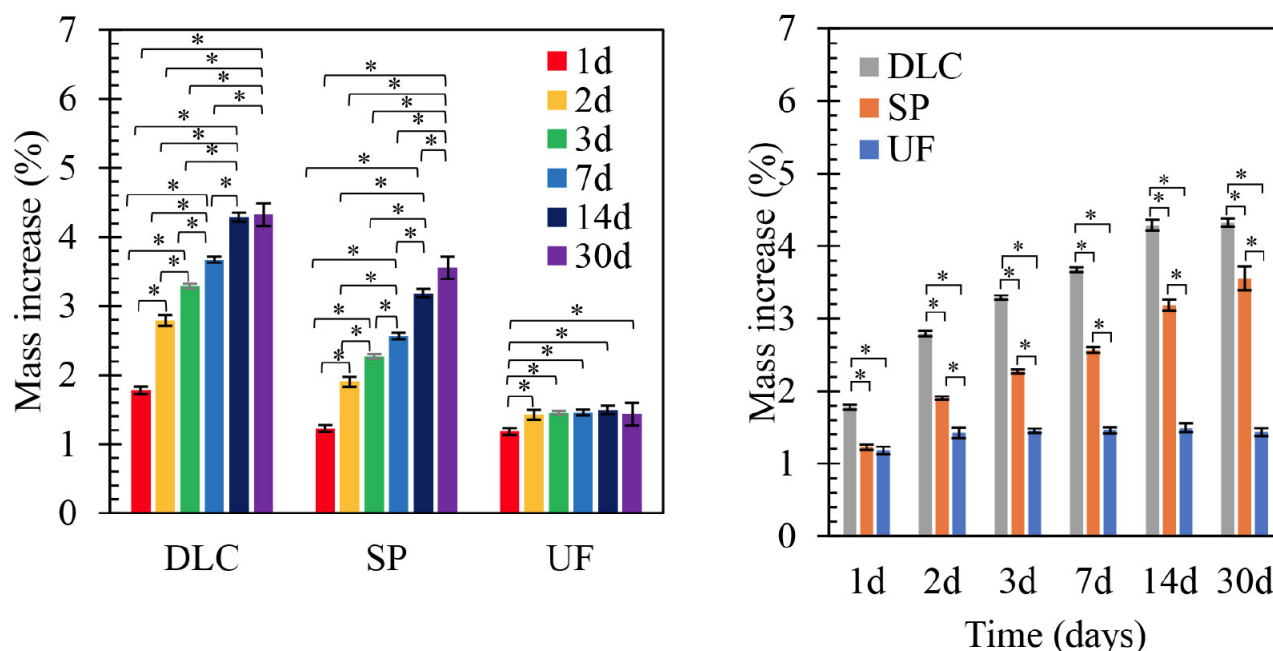
Fig. (2). Mean water absorption profiles of the tested materials after immersion for 1, 2, 3, 7, 14, and 30 days. The left panel shows the percentage of mass increase (y-axis) over time (x-axis: days) for each material, while the right panel compares materials at each time point. DLC: Dental LT Clear; SP: Splint; UF: Uni Fast III. *$p < 0.05$ indicates statistically significant differences among groups and time points.
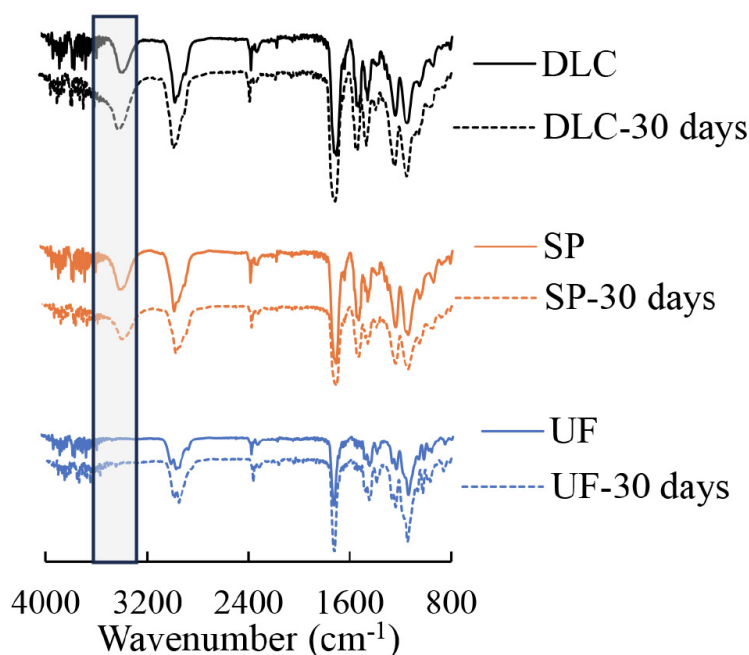

Fig. (3). The FTIR spectra of specimens before and after 30 days of immersion in artificial saliva. The x-axis represents the wavenumber (cm^{-1}), and the y-axis represents transmittance (%). The highlighted region at ~3,600 cm^{-1} reflects changes in the intensity of the hydroxyl (–OH) group absorption band. Solid lines correspond to day 0 and dashed lines to day 30. DLC: Dental LT Clear; SP: Splint; UF: Uni Fast III. *$p < 0.05$ indicates statistically significant differences.
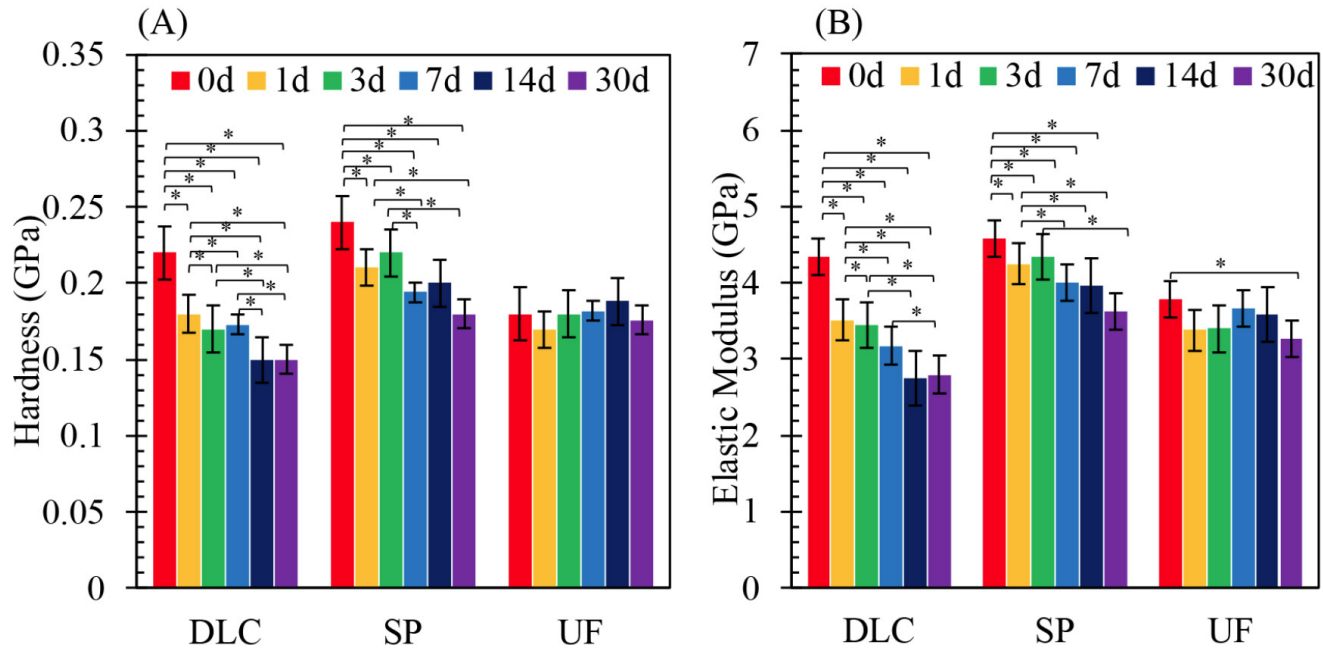
Fig. (4). Nanoindentation results showing the mean hardness (**A**) and elastic modulus (**B**) values measured at 0, 1, 3, 7, 14, and 30 days. The y-axis shows hardness (GPa) or elastic modulus (GPa), and the x-axis represents the immersion duration (days). DLC: Dental LT Clear; SP: Splint; UF: Uni Fast III. *$p < 0.05$ indicates statistically significant differences among groups and time points. The mean hardness and elastic modulus values yielded by the nanoindentation test at 1, 2, 3, 7, 14, and 30 days. DLC: Dental LT Clear; SP: Splint; UF: Uni Fast III (*$p < 0.05$).

4. DISCUSSION

During orthodontic/orthognathic surgery, splints are essential to position the maxilla and mandible precisely during both surgery and initial recovery. The polymeric splint materials must be resistant to possible water-mediated deterioration of the mechanical properties, decomposition, and water absorption in the humid oral environment [15-18]. Therefore, this study examined changes in the physical properties over time, especially water absorption of 3D-printed surgical splint materials.

The elastic modulus, bending strengths, and elongations of both 3D-printing materials revealed by the three-point bending test were similar, and significantly greater than those of conventional PMMA-based resin. The 3D-printing materials would thus be more resistant to stress, especially that generated by the muscles associated with functional mandibular movement [19]. The 3D-printed materials exhibited excellent elongation (ductility); this would reduce the risk of splint chipping during inter-maxillary fixation. These findings are similar to those reported by a recent study on 3D-printed denture base resins [20].

However, FTIR revealed that the 3D-printing materials absorbed significantly more water from artificial saliva than did the conventional PMMA-based resin, perhaps reflecting water penetration into the polymer structure; this may be reduced if the printing layers were thinner [20]. Similarly, recent studies evaluating the water absorption of 3D-printing materials, milled and injection

materials [21], or thermoplastic materials [22] have reported that 3D-printed samples exhibited higher water absorption. The correlations between the mechanical properties (hardness and the elastic modulus) of the 3D-printed materials, revealed by the nanoindentation test, and material degradation over time, differed significantly from those of the conventional PMMA-based resin. These results contrast with those of a previous report that examined monomer release *in vitro* from 3D-surgical splints; such release was less than that from conventional PMMA-based specimens [23]. One possible explanation is that the experiments and materials differed. Of all released monomers, most would be expected to have been surface-located. Our nanoindentation tests quantified the mechanical properties of the surface layer. Further research is needed to clarify the relationship between monomer release and splint mechanical properties.

The results of this study revealed that the 3D-printed materials exhibited significant degradation of mechanical properties upon immersion compared to conventional PMMA-based resin. A recent cohort study on bimaxillary orthognathic surgery reported errors of approximately 0.5 mm in the maxilla and 1 mm in the mandible compared to the designed surgical plan [17]. Considering this error value, the clinical impact of the differences in material properties between the 3D-printed material and PMMA appears to be minimal. However, further prospective comparative studies, such as randomized controlled trials (RCTs), are likely needed to confirm this.

CONCLUSION

Under the conditions of this study, the following conclusions can be drawn:

- The elastic modulus, bending strengths, and elongations of both 3D-printing materials revealed by the three-point bending test were similar and significantly greater than those of conventional PMMA-based resin.
- 3D-printed materials exhibited significantly more water absorption and degradation in artificial saliva than did a conventional PMMA-based resin.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: M.I.: Study conception and design; Y.M., Y.E., K.E. and E.E.Z.: Data collection; Y.M., Y.E., K.E. and E.E.Z.: Data analysis or interpretation; M.I.: Methodology: Y.M. and E.E.Z.: Investigation; M.I.: Draft manuscript. All authors reviewed the results and approved the final version of the manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

HUMAN AND ANIMAL RIGHTS

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The data supporting the findings of this study are presented within the article.

FUNDING

None.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

REFERENCES

[1]   Otto T, Schneider D. Long-term clinical results of chairside Cerec CAD/CAM inlays and onlays: A case series. Int J Prosthodont 2008; 21(1): 53-9.
http://dx.doi.org/10.5167/uzh-12825 PMID: 18350948

[2]   Peroz S, Spies BC, Adali U, Beuer F, Wesemann C. Measured accuracy of intraoral scanners is highly dependent on methodical factors. J Prosthodont Res 2022; 66(2): 318-25.
http://dx.doi.org/10.2186/jpr.JPR_D_21_00023 PMID: 34456211

[3]   Ferraro JM, Falter J, Lee S, *et al.* Accuracy of three-dimensional printed models derived from cone-beam computed tomography. Angle Orthod 2022; 92(6): 722-7.
http://dx.doi.org/10.2319/021122-128.1 PMID: 35852459

[4]   Sharifi A, Jones R, Ayoub A, *et al.* How accurate is model planning for orthognathic surgery? Int J Oral Maxillofac Surg 2008; 37(12): 1089-93.
http://dx.doi.org/10.1016/j.ijom.2008.06.011 PMID: 18760569

[5]   Mascarenhas W, Makhoul N. Efficient in-house 3D printing of an orthognathic splint for single-jaw cases. Int J Oral Maxillofac Surg 2021; 50(8): 1075-7.
http://dx.doi.org/10.1016/j.ijom.2020.12.016 PMID: 33446444

[6]   Ghai S, Sharma Y, Jain N, Satpathy M, Pillai AK. Use of 3-D printing technologies in craniomaxillofacial surgery: A review. Oral Maxillofac Surg 2018; 22(3): 249-59.
http://dx.doi.org/10.1007/s10006-018-0704-z PMID: 29797107

[7]   Metzger MC, Hohlweg-Majert B, Schwarz U, Teschner M, Hammer B, Schmelzeisen R. Manufacturing splints for orthognathic surgery using a three-dimensional printer. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2008; 105(2): e1-7.
http://dx.doi.org/10.1016/j.tripleo.2007.07.040 PMID: 18230371

[8]   Aboul-Hosn Centenero S, Hernández-Alfaro F. 3D planning in orthognathic surgery: CAD/CAM surgical splints and prediction of the soft and hard tissues results – Our experience in 16 cases. J Craniomaxillofac Surg 2012; 40(2): 162-8.
http://dx.doi.org/10.1016/j.jcms.2011.03.014 PMID: 21458285

[9]   Schouman T, Rouch P, Imholz B, Fasel J, Courvoisier D, Scolozzi P. Accuracy evaluation of CAD/CAM generated splints in orthognathic surgery: A cadaveric study. Head Face Med 2015; 11(1): 24.
http://dx.doi.org/10.1186/s13005-015-0082-9 PMID: 26209339

[10] Park JH, Lee YB, Kim SY, Kim HJ, Jung YS, Jung HD. Accuracy of modified CAD/CAM generated wafer for orthognathic surgery. PLoS One 2019; 14(5): e0216945.
http://dx.doi.org/10.1371/journal.pone.0216945 PMID: 31095627

[11] Danesh G, Lippold C, Mischke KL, *et al.* Polymerization characteristics of light- and auto-curing resins for individual splints. Dent Mater 2006; 22(5): 426-33.
http://dx.doi.org/10.1016/j.dental.2005.04.032 PMID: 16045980

[12] Prpic V, Spehar F, Stajdohar D, Bjelica R, Cimic S, Par M. Mechanical properties of 3d-printed occlusal splint materials. Dent J 2023; 11(8): 199.
http://dx.doi.org/10.3390/dj11080199 PMID: 37623295

[13] Dimitrova M, Vlahova A, Hristov I, *et al.* Evaluation of water sorption and solubility of 3D-Printed, CAD/CAM milled, and PMMA denture base materials subjected to artificial aging. J Compos Sci 2023; 7(8): 339.
http://dx.doi.org/10.3390/jcs7080339

[14] Abad-Coronel C, Ruano Espinosa C, Placios Ordenez S. Comparative analysis between conventional acrylic, CAD/CAM Milled, and 3D CAD/CAM printed occlusal splints. Materials 2023; 16(18): 6269.
http://dx.doi.org/10.3390/ma16186269 PMID: 37763547 PMCID: PMC10532716

[15] Perea-Lowery L, Gibreel M, Vallittu PK, Lassila LV. 3D-printed *vs.* heat-polymerizing and autopolymerizing denture base acrylic resins. Materials 2021; 14(19): 5781.
http://dx.doi.org/10.3390/ma14195781 PMID: 34640178

[16] Gad MM, Alshehri SZ, Alhamid SA, *et al.* Water sorption, solubility, and translucency of 3d-printed denture base resins. Dent J 2022; 10(3): 42.
http://dx.doi.org/10.3390/dj10030042 PMID: 35323244 PMCID: PMC8947006

[17] Abel AR, Ho K, Neugarten JM. What is the accuracy of bimaxillary orthognathic surgery using occlusally-based guides and patient-specific fixation in both jaws? A cohort study and discussion of surgical techniques. J Oral Maxillofac Surg 2022; 80(12): 1912-26.
http://dx.doi.org/10.1016/j.joms.2022.08.009 PMID: 36116544

[18] Wang X, Mu M, Yan J, Han B, Ye R, Guo G. 3D printing materials and 3D printed surgical devices in oral and maxillofacial surgery: Design, workflow and effectiveness. Regen Biomater 2024; 11: rbae066.
http://dx.doi.org/10.1093/rb/rbae066 PMID: 39169972

[19]   Alhotan A, Yates J, Zidan S, Haider J, Silikas N. Assessing fracture toughness and impact strength of PMMA reinforced with nano-particles and fibre as advanced denture base materials. Materials 2021; 14(15): 4127.
http://dx.doi.org/10.3390/ma14154127 PMID: 34361320

[20]   Greil V, Mayinger F, Reymus M, Stawarczyk B. Water sorption, water slubility, degree of conversion, elastic indentation modulus, edge chipping resistance and flexural strength of 3D-printed. J Mech Behav Biomed Mater 2023; 137: 105565.
http://dx.doi.org/10.1016/j.jmbbm.2022.105565 PMID: 36401933

[21]   Neoh SP, Khantachawana A, Chintavalakorn R, Santiwong P, Srikhirin T. Comparison of physical, mechanical, and optical properties between thermoplastic materials and 3-dimensional printing resins for orthodontic clear retainers. Am J Orthod Dentofacial Orthop 2025; 167(1): 95-109.e1.
http://dx.doi.org/10.1016/j.ajodo.2024.06.010 PMID: 39709226

[22]   Maleki T, Meinen J, Coldea A, Reymus M, Edelhoff D, Stawarczyk B. Mechanical and physical properties of splint materials for oral appliances produced by additive, subtractive and conventional manufacturing. Dent Mater 2024; 40(8): 1171-83.
http://dx.doi.org/10.1016/j.dental.2024.05.030 PMID: 38851965

[23]   Sha Y, Quah B, Sng TJH, Yong CW, Islam I. Are 3D printed resin surgical splints safe to use in the mouth? A comparative in *vitro* study. Annals of 3D Printed Medicine 2023; 9: 100097.
http://dx.doi.org/10.1016/j.stlm.2022.100097