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RESEARCH AND EDUCATION

Can nonhazardous postprocessing cleaning solutions enable adequate surface properties for printed dental casts in different resins?

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ABSTRACT

Statement of problem. Printed casts and dental devices and prostheses are increasingly being used, and the ecological impact of additive manufacturing should be considered in addition to the fabrication accuracy and surface properties of the printed object. To overcome the ecological drawbacks of alcohol postprocessing, water-washable, 3-dimensionally (3D) printable cast resins and postprocessing cleaning solutions that do not include alcohol have been introduced. However, whether using only water rather than chemical solvents would enable the surface smoothness and hardness required for accurate diagnostic and prosthetic procedures is unknown.

Purpose. The purpose of this in vitro study was to evaluate the effect of resin type (water-washable or nonwater washable) and postprocessing cleaning solution on the surface roughness and microhardness of 3D printed dental cast resins.

Material and methods. One hundred eight disk-shaped specimens (Ø10×2 mm) were additively manufactured (AM) from 3 dental cast resins: 2 water-washable (Epax (WW1) and Phrozen (WW2)) and 1 nonwater-washable resin (KeyModel Ultra resin-beige (NWW)) with a printer (n=36). Specimens in each resin type were divided into 3 groups for the application of postprocessing cleaning solution (water, 98% isopropyl alcohol [IPA] or methyl ether solvent) and polymerized after cleaning. The surface roughness (R_a, µm) and Vickers microhardness (HV) were measured. Laser microscope images were made of 1 specimen from each group.

Results. NWW-IPA (control group) had a similar R_a to WW2-water (P=.81) and WW2-methyl ether solvent (P=.511). NWW-IPA had lower HV than WW2-water (P<.001) and WW1-methyl ether solvent (P=.001). Solutions had no significant effect on the R_a of WW1 (P≥.554) and WW2 (P≥.805). WW1 had higher surface irregularities with water, whereas no significant difference was visually observed with IPA or methyl ether solvent. Solutions had a similar effect on the surface of WW2 when evaluated visually with the laser microscope.

Conclusions. Resin type and postprocessing cleaning solution affected the surface roughness and microhardness of 3D printed dental cast resins, except for the surface roughness of tested water-washable resins. Water or methyl ether solvent cleaned water-washable resin (WW2) had surface roughness and hardness similar to commonly used nonwater-washable cast resin. (J Prosthet Dent 2025;133:893-902)

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Clinical Implications

Water-washable 3D printed dental cast resin (WW2) postprocessed with water or methyl ether solvent can be a promising alternative to conventional 3D printed cast resin postprocessed with IPA in terms of surface roughness and hardness of the casts. Postprocessing WW2 cast resin with water or methyl ether solvent could enable ecologically friendly and sustainable cast fabrication and address the drawbacks of the hazardous impacts of IPA postprocessing.

Advances in computer-aided design and computer-aided manufacturing (CAD-CAM) technology has made the digital cast an alternative to the conventional stone cast.[1–3] However, physical casts are still needed for diagnostic purposes or the treatment of complex patient situations, particularly in prosthodontics and orthodontics, and removable die fabrication for veneering or esthetic and functional adjustments.[4–8]

Additive manufacturing (AM) is becoming common for the fabrication of polymer dental casts.[1,9,10] However, potential issues related to the use of resin and fluids associated with AM should be taken into consideration.[11,12] Because of their frequent and widespread use worldwide, the fabrication process of dental casts should be sustainable, nonhazardous, and ecologically friendly.[13–15] The pollution impact, production of nontoxic wastewater, emissions, and energy consumption should be considered during material selection for AM, in addition to the printed object's fabrication accuracy and surface properties.[13–15] The need to postprocess AM casts with primarily isopropyl alcohol or ethanol[11,12] and their inhalation in the work environment can be hazardous. An animal study revealed that repeated exposure to isopropanol resulted in several toxic effects, including a transient decrease in body weight, an increase in motor activity, changes in clinical pathology parameters, and a microscopic renal change.[16] Therefore, addressing AM's hazardous implications is essential for human health and the environment.[17] To overcome the drawbacks of alcohol postprocessing, water-washable (WW) 3D printable cast resins and postprocessing cleaning solutions that do not include alcohol have been introduced.[18–22] These resins and cleaning solutions may have lower odor and hazardous air pollutants, making them safer and more straightforward to use.[14]

Aside from the need for ecologically friendly and sustainable manufacturing, cast details can be clinically crucial; margins of removable dies should be smooth and precise to simulate clinical situations and for dental professionals to evaluate and adjust the fit of fixed prostheses.[1,23] When the margins of removable dies have surface irregularities, the finish line of the prostheses may be altered.[24] The cast resin should also have adequate surface hardness to withstand damage on critical surfaces caused by repeated insertion and removal of removable dies into casts or insertion and removal of the restorations during adjustments.[23] In addition, the durability and stability of the surfaces of casts and removable dies are crucial to withstand different storage times and conditions.[1,25] Therefore, the surface characteristics of cast resins, including surface roughness and hardness, are critical to successful prosthetic treatments.

Knowledge of the manufacturing trinomial (technology, printer, and material selected) and printing strategy impact the printed object's accuracy and physical and mechanical properties, which may improve the outcome of an AM dental appliance.[26] However, whether using only water rather than chemical solvents would enable adequate surface smoothness and hardness for the WW casts required for accurate diagnostics and prosthetic work is unknown. Unpolymerized resin remnants on dental casts may compromise their surface characteristics if not cleaned adequately. To the authors' knowledge, only 1 study evaluated the effect of postprocessing cleaning solution and rinsing times on the manufacturing accuracy of a nonwater washable (NWW) 3D printed cast resin.[27] However, studies that evaluated WW 3D printed cast resins and postprocessing cleaning solutions for resins' resulting surface roughness and hardness are lacking. Therefore, this study aimed to assess the effect of resin type (WW versus NWW) and postprocessing cleaning solution (water, 98% isopropyl alcohol [IPA], or methyl ether solvent) on the surface roughness and microhardness of 3D printed cast resins. NWW with IPA was used as the control group, as this material is a commonly used AM dental cast resin and is frequently postprocessed with IPA. The null hypothesis was that the dental cast resin type and postprocessing cleaning solution would not affect the surface roughness or microhardness of dental casts. The findings of this study may broaden the knowledge of the surface properties of dental casts when potentially ecofriendly resins and postprocessing cleaning solutions are used to minimize the long-term adverse environmental impact of the fabrication process.

MATERIAL AND METHODS

A total of 108 disk-shaped specimens (Ø10×2 mm) were AM from 3 different cast resins: 2 WW resins (Epax water-washable dental cast resin; Epax 3D) (WW1) and Phrozen water-washable dental cast resin; Phrozen Tech

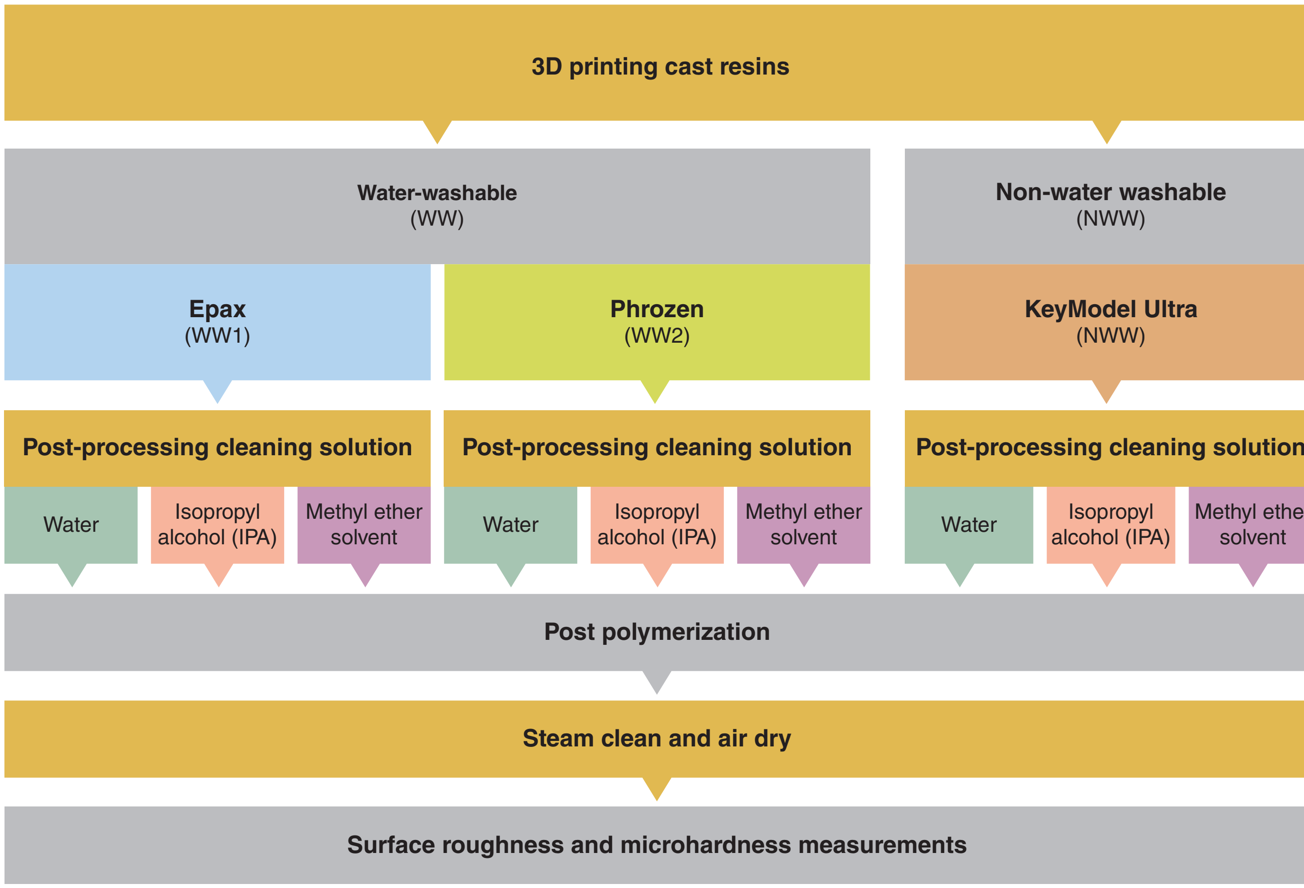

Figure 1. Overview of study.

Co, Ltd) (WW2) and 1 NWW resin (KeyModel Ultra resin-beige; Keystone Industries) (NWW) (n=36). The specimens were printed using a liquid crystal display (LCD) printer (Phrozen Sonic Mini 4K; Phrozen Tech Co, Ltd.) with a layer thickness of 100 µm. The printing parameters were selected in a 3D printer software program (Chitubox V1.9.4; Phrozen Tech Co, Ltd) for the respective cast resin according to the manufacturer's recommendation. A vertical build orientation (90-degree print orientation)[28,29] was used to fabricate the specimens. After generating the support structures, this configuration was replicated 12 times per material-postprocessing cleaning solution pair. Twelve specimens per material-postprocessing cleaning solution group were determined based on a priori power analysis that used pilot experiments on 5 specimens from each group: for 95% CI (1-), 95% power (1-), and effect size of f=0.718. Figure 1 shows an overview of the study.

After printing, the specimens were divided into 3 groups for different postprocessing cleaning solutions. In the water group, all resin specimens were washed with tap water for 1 minute without detergent or other cleaning agents, followed by another 5 minutes of ultrasonic cleaning in fresh water.[30] In the IPA group, WW resin specimens were washed in 98% IPA (Isopropanolum resin; Cristoffel-Apotheke AG) for 2 minutes, followed by another 3 minutes of ultrasonic cleaning in fresh 98% IPA. For the NWW resin, the specimens were washed in the same 98% IPA for 2 minutes, followed by another 3 minutes of ultrasonic cleaning in fresh 98% IPA.[29] The NWW resin postprocessed with IPA was used as the control group, as NWW is recommended to be cleaned with IPA by its manufacturer. In the solvent group, all resin specimens were washed in a solvent based on methyl ethers (Weiton-3D Resin Cleaner; Johannes Weithas GmbH Co.KG) for 2 minutes, followed by another 3 minutes of ultrasonic cleaning in a fresh solution.[31]

Approximately 10 minutes after washing, the specimens were postpolymerized according to the manufacturer's recommendations. The WW resin specimens were postpolymerized by using an ultraviolet light box (Asiga flash; Asiga) for 30 minutes (15 minutes per surface). The NWW resin specimens were polymerized by using a xenon lamp-polymerization unit (a total of 4000 lighting exposures; 2000 for each surface) without nitrogen gas atmosphere (Otoflash G171; NK Optical GmbH). After fabrication, all specimens were steam-cleaned for 10 seconds and air dried for 10 seconds (Fig. 2).

Figure 2. Representative images of specimens from each material-post-processing cleaning solution pair.

Surface roughness (Ra in µm) was measured with a noncontact profilometer (FRT MicroProf 100; Fries Research Technology GmbH).[32] A total of 6 traces (3 horizontal and 3 vertical; 1 mm apart from each other) were measured with a 5.5-mm trace length, 5501-point-line pixel density, 3-nm resolution in z-dimension, and 0.8-mm[33,34] cut-off wavelength Lc.[32] The average surface irregularity of traces was measured with the software program of the profilometer (Mark III; Fries Research Technology GmbH) to calculate average Ra values per specimen.[32]

Microhardness (weight/area of indentation, HV) was measured with a Vickers hardness tester and a pyramid-shaped diamond indenter (Fischerscope HM2000; Helmut-Fischer). Five measurements were made on each specimen (0.49-N load for 30 seconds dwell time), and the average of these measurements was calculated.[35] Laser microscope images of 1 specimen from each material-postprocessing cleaning solution pair were made using a laser digital microscope (Keyence Laser Microscope VK-X3000 Series; Keyence Corp) at a ×20 magnification.

The normality of data was analyzed by using the Kolmogorov-Smirnov test. Because of the nonnormal distribution of R_a and HV values, logarithmic transformation was performed to normalize the data. Two-way analysis of variance followed by post hoc Tukey HSD tests were used to analyze the differences among the material type and postprocessing cleaning solutions and the interaction between material types and postprocessing cleaning solutions. All analyses were performed by using statistical analysis software program (Minitab Software V.17; Minitab) (α=.05).

RESULTS

For R_a, according to the 2-way ANOVA, a significant interaction was found between material type and post-processing cleaning solution (df=4, adj MS=2.435, F=14.17, P<.001). Table 1 summarizes the descriptive

Table 1. Mean ±standard deviation values of surface roughness (R_a, µm) values for each material-post-processing cleaning solution pair

	WW1	WW2	NWW	Total
Water	0.6 ±0.2^{ab}	0.3 ±0.2^{cd}	0.8 ±0.3^{a}	0.6 ±0.3^{A}
IPA	0.5 ±0.1^{ab}	0.4 ±0.2^{bc}	0.2 ±0.2^{d}	0.4 ±0.2^{B}
Methyl ether solvent	0.4 ±0.1^{bc}	0.3 ±0.2^{cd}	0.3 ±0.2^{cd}	0.3 ±0.1^{B}
Total	0.5 ±0.2^{A}	0.3 ±0.2^{B}	0.4 ±0.3^{B}	0.4 ±0.3

IPA, isopropyl alcohol; NWW, non-water washable 3D printed cast resin: KeyModel Ultra resin-beige, Keystone Industries; R_a, surface roughness; WW1, Epax water-washable resin, Epax 3D; WW2, Phrozen resin-water washable dental cast, Phrozen. Different superscript letters indicate significant differences. Uppercase letters indicate significant differences for total values among materials (rows) or post-processing cleaning solutions (columns). Lowercase letters indicate significant differences among material-post-processing cleaning solution pairs (P<.05).

Table 2. Mean ±standard deviation values of Vickers microhardness (HV) for each material-post-processing cleaning solution pair

	WW1	WW2	NWW	Total
Water	7.4 ± 2.7^{ef}	12.4 ± 1.5^{bc}	5.6 ± 1.3^{f}	8.5 ± 3.5^{C}
IPA	13.6 ± 2.1^{b}	29.3 ± 8^{a}	7.4 ± 1^{de}	16.8 ± 10.4^{A}
Methyl ether solvent	11.3 ± 1.5^{bc}	9.6 ± 1.3^{cd}	6.9 ± 0.4^{ef}	9.3 ± 2.1^{B}
Total	10.8 ± 3.3^{B}	17.1 ± 10^{A}	6.6 ± 1.2^{C}	11.5 ± 7.4

HV, Vickers hardness; IPA, isopropyl alcohol; NWW, non-water washable 3D printed cast resin: KeyModel Ultra resin-beige, Keystone Industries; R_a, surface roughness; WW1, Epax water-washable resin, Epax 3D; WW2, Phrozen resin-water washable dental cast, Phrozen. Different superscript letters indicate significant differences. Uppercase letters indicate significant differences for total values among materials (rows) or post-processing cleaning solutions (columns). Lowercase letters indicate significant differences among material-post-processing cleaning solution pairs ($P<.05$).

statistics of R_a (µm) values. NWW with IPA (control group) had a lower R_a than WW1 with water ($P<.001$) and WW1 with methyl ether solvent ($P=.016$), whereas it had a similar R_a to WW2 with water ($P=.81$) and WW2 with methyl ether solvent ($P=.511$).

The effect of postprocessing solution on cast resins' R_a varied depending on the resin; NWW had the highest R_a with water ($P<.001$), whereas the difference between IPA and methyl ether solvent was not significant ($P=.992$). The R_a of WW1 ($P\geq.554$) and WW2 ($P\geq.805$) was not significantly different when different post-processing cleaning solutions were used (Table 1).

Resin type significantly affected the R_a when the same postprocessing cleaning solution was used. WW2 had a lower R_a than WW1 and NWW with water ($P\leq.004$), while NWW had a lower R_a than WW1 and WW2 with IPA ($P\leq.049$). Resins showed similar R_a with methyl ether solvent ($P\geq.175$), while NWW had a lower R_a than WW1 and WW2 with IPA ($P\leq.049$).

For Vickers microhardness (HV), according to 2-way ANOVA, material type and postprocessing cleaning solution had a significant interaction (df=4, adj MS=1.072, F=19.06, $P<.001$). Table 2 summarizes the descriptive statistics of Vickers microhardness (HV) values. NWW with IPA (control group) had a similar HV to WW1 with water ($P=.998$) and WW2 with methyl ether solvent ($P=.160$), whereas it had a lower HV than WW2 with water ($P<.001$) and WW1 with methyl ether solvent ($P=.001$).

The postprocessing cleaning solution's effect on cast resins' HV was significant for all resins (Table 2); WW2 had the highest HV with IPA ($P<.001$), but the difference between water and methyl ether solvent was not significant ($P=.197$). WW1 had the lowest HV with water ($P<.001$), whereas the difference between IPA and methyl ether solvent was not significant (P=.585). NWW-IPA had higher HV than with NWW-water ($P=.034$).

Resin type significantly affected the HV when the same postprocessing cleaning solution was used. With water, WW2 had the highest HV ($P<.001$), whereas WW1 and NWW had similar HV ($P=.223$). With IPA, WW2 had the highest HV ($P<.001$), while NWW had the lowest HV ($P<.001$). With methyl ether solvent, NWW had the lowest HV ($P\leq.030$), whereas WW1 and WW2 had similar HVs ($P=.783$).

According to the laser microscope images (Figs. 3 and 4), NWW-water had surface irregularities in the form of bubbles and potential resin residue compared with other surface treatments, whereas it had smoother surfaces when IPA or methyl ether solvents were used. However, WW2-IPA had surface irregularities in the form of bubbles and potential resin residue compared with other surface treatments, whereas, it had smoother surfaces when water or methyl ether solvent were used. WW1-methyl ether solvent and IPA had smoother surfaces with fewer scratches compared with WW1-water.

DISCUSSION

The results of this study suggested that the post-processing cleaning solution significantly impacted the surface roughness and microhardness of tested 3D printed dental cast resins, except for the surface roughness of WW1 and WW2. In addition, the post-processing cleaning solution led to significant differences in surface roughness and microhardness when 3D printed dental cast resins were compared. Therefore, the null hypothesis that the dental cast resin type and postprocessing cleaning solution would not affect the surface roughness or microhardness of dental casts was rejected.

AM dental casts are commonly manufactured from NWW resins, and IPA is frequently used as the post-processing cleaning solution. Therefore, the present study used NWW with IPA as the control group. Postprocessing cleaning solutions had a similar effect on the roughness of WW1 and WW2, but WW1 had slightly higher surface roughness with water, and WW2 with IPA, which was not significant ($P>.05$). These findings were consistent with the laser microscope images, where WW1 had higher surface irregularities with water, while having a similar surface texture with IPA and methyl ether solvent. The images showed that WW2 with IPA had surface irregularities in the form of bubbles and potential residue, while the surface texture was similar to when water or methyl ether solvent were used. WW1 had similar microhardness when IPA or methyl ether

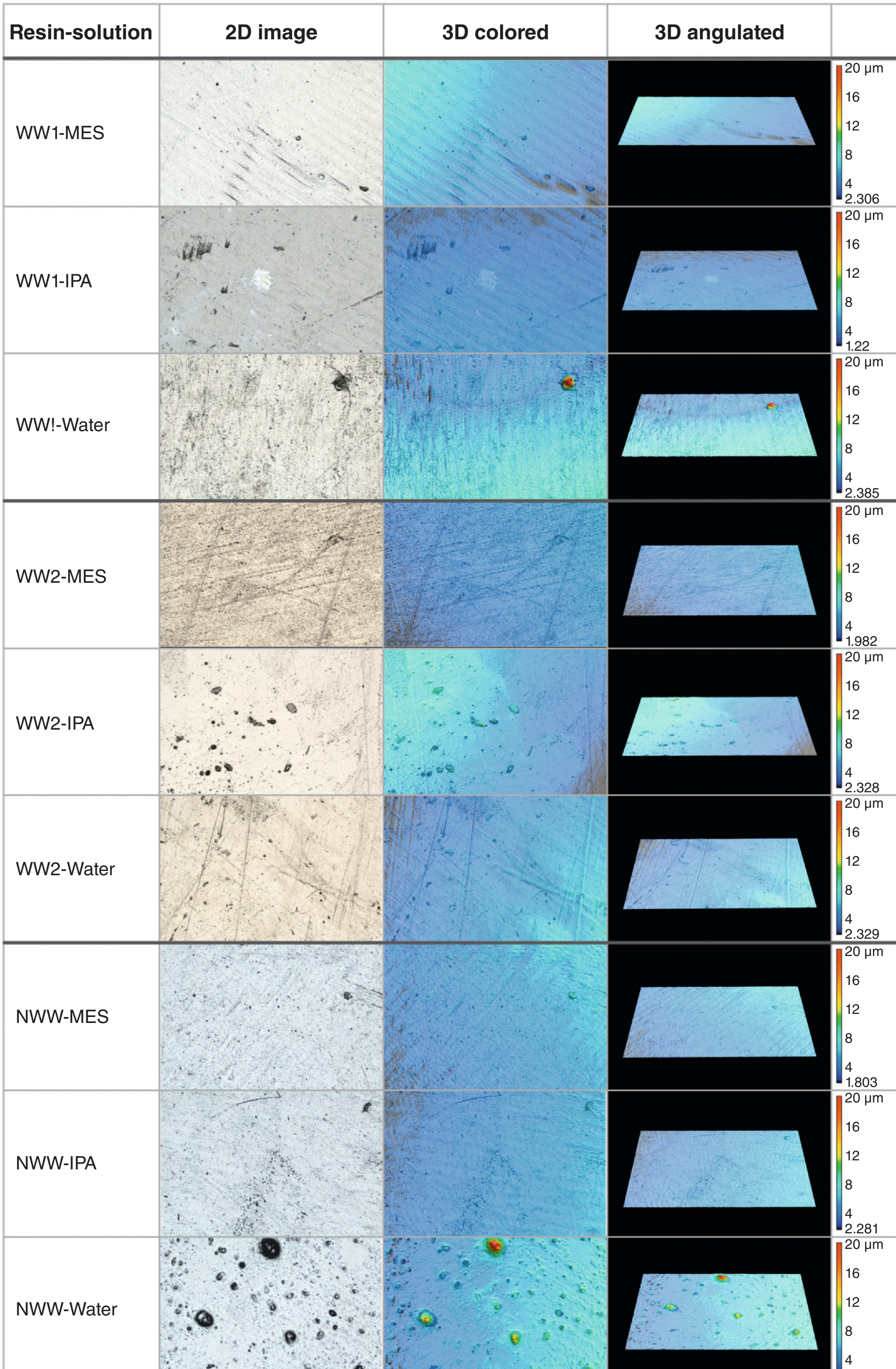

Figure 3. Laser microscope images of specimens (original magnification ×20) from each material-post-processing cleaning solution pair. IPA, isopropyl alcohol; MES, methyl ether solvent; NWW, non-water washable 3D printed cast resin: KeyModel Ultra resin-beige, Keystone Industries; WW1, Epax water-washable resin, Epax 3D; WW2, Phrozen resin-water washable dental cast, Phrozen.

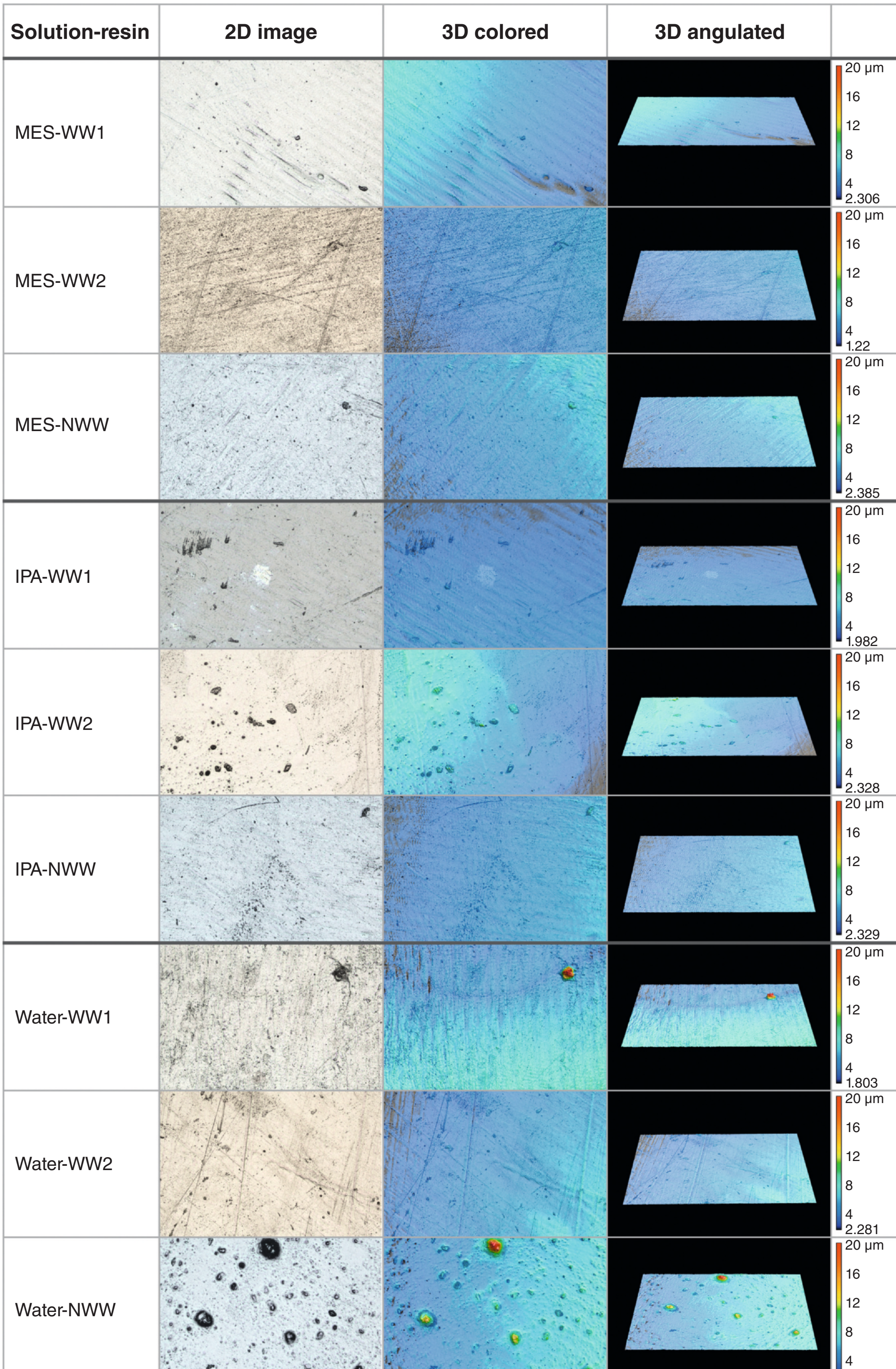

Figure 4. Laser microscope images of specimens (original magnification ×20) from each postprocessing cleaning solution-material pair. IPA, isopropyl alcohol; MES, methyl ether solvent; NWW, non-water washable 3D printed cast resin: KeyModel Ultra resin-beige, Keystone Industries; WW1, Epax water-washable resin, Epax 3D; WW2, Phrozen resin-water washable dental cast, Phrozen.

solvent was used, whereas it had the lowest microhardness with water. WW2 had similar microhardness when water or methyl ether solvent was used, whereas it had the highest microhardness with IPA. The difference in microhardness results between tested WW resins might be because of the difference in resin compositions.

NWW cleaned with water had the highest surface roughness and lower microhardness than IPA. However, when IPA or methyl ether solvent was used, NWW had similar surface roughness and microhardness. These findings were consistent with laser microscope images, where NWW had increased surface irregularities in the form of bubbles showing potential resin residue with water compared with the other postprocessing cleaning solutions.

All aspects of AM are important, including waste products, as hazardous chemical waste at the end of the AM process due to excess unpolymerized resin waste can be concerning.[17] The findings of this study provide information to clinicians and dental laboratory technicians for alternative postprocessing cleaning solutions for AM dental casts. Avoiding the use of IPA to post-process casts can be ecologically advantageous if the negative environmental impact of cleaning solution waste is minimized.[36,37] Although IPA is the most commonly used solution for cleaning unpolymerized resin from 3D printed objects, it is flammable, has a high vapor pressure, and is highly volatile.[36,37] Therefore, it is essential to take safety precautions when handling IPA.[11,38] The tested methyl ether solvent does not require the same safety precautions as IPA because it is an odorless, nontoxic, nonflammable, and biodegradable liquid with a low vapor pressure.[31] The manufacturer claims that it can be reused up to 5 times.[31] Therefore, the methyl ether solvent can be considered more environmentally friendly than IPA. The use of tap water as a postprocessing cleaning solution is the most straightforward and cost-effective, being the most ecofriendly solution.[17]

Considering the findings, water or methyl ether solvent postprocessing cleaning solutions can be used for WW2, while methyl ether solvent or IPA can be used for WW1 and NWW. Moreover, WW2 resin, either cleaned with water or methyl ether solvent, can be accepted as an alternative for dental cast fabrication over NWW (with IPA, the control group), considering its comparable surface roughness and microhardness results, providing ecologically friendly and sustainable dental cast fabrication.

The authors are unaware of previous studies that evaluated the effect of cleaning solutions on the surface properties of WW and NWW 3D printed casts. Therefore, directly comparing present study results to prior studies is difficult. Previous studies reported that cleaning solutions (butyldiglycol-based solution, IPA, and centrifugation) had a significant effect on shear bond strength between the resin cement and 3D printed interim resin[39]; manufacturing accuracy of vat-polymerized dental materials (tripropylene glycol monomethyl ether (TPM) and IPA)[27]; both surface hardness and flexural strength of resins for interim use (acetone, butyl glycol, ethanol, IPA, Yellow Magic 7, or centrifugal force)[20]; the flexural strength of resins for interim use (91% IPA, 99% IPA, bio-ethyl alcohol 100%, tripropylene glycol monomethyl ether (TPM) 100%, and water-miscible formula)[40]; and the fracture load of interim crowns (isopropanol, Yellow Magic 7, or centrifugal force).[19] Hwangbo et al reported that cleaning solution (90% IPA and 95% TPM) had no significant effect on the mechanical properties of 3D printed resins used for denture teeth and fixed dental prostheses, whereas cleaning time had a significant impact.[11] Consistent with the present study, no cracks or mechanical damage were observed because of the cleaning solution[11]; nevertheless, variations in surface characteristics between tested 3D printed resins were found. This study[11] reported the lower surface penetration of TPM into polymerized resin than IPA. Also, IPA did not penetrate the surface during 90 minutes of washing and caused irreversible deformation. Because WW dental resins are more hydrophilic,[21,22] during the postprocessing of WW 3D printed cast resins, water may be stored between consecutive print layers, potentially leading to cracks and layer splitting. The water storage may result in a brittle surface on thinner parts or increase surface irregularities. When the printed dental casts encounter water after printing, moisture during storage or transportation, degradation, or softening may occur.[11] However, IPA can be expected to evaporate rather than remain between consecutive print layers, considering a maximum of 10 minutes of cleaning applied in the present study. The present study's surface roughness and microhardness results substantiate this hypothesis, as IPA resulted in increased surface roughness and higher microhardness, values similar to when WW resins were water-cleaned.

The present study results should be interpreted considering the manufacturing trinomial and printing strategy used, as generalizations are not recommended if a different technology, printer, or material is used. Different results may be expected with other printer technologies, printers, and materials, as well as printing parameters such as printing structures and slicing methods, which have been reported to have a considerable influence on the surface roughness, printing accuracy, and mechanical properties of the manufactured dental device.[26] Limitations of this study included that only 1 brand of NWW resin was tested. Resins with different chemical compositions from other manufacturers might be impacted differently by varying cleaning solutions. Future studies should broaden the present study's findings by testing various resins and different material properties. The use of these casts for diagnostic or treatment purposes should be further evaluated in terms of manufacturing accuracy, print quality, effect of storage condition, and dimensional stability. Although manufacturing and polymerization protocols were standardized for each group to focus on the impact of cleaning solutions on distinct types of resins, future studies should evaluate the effect of different combinations of manufacturing protocols on various material properties. In addition, other cleaning solutions and methods may be involved in future studies. AM technology and materials are rapidly evolving, with new resins and cleaning solutions coming to the market. Currently, water-washable resins are available only for dental casts, crowns, and fixed partial dentures.[37] To the authors' knowledge, only 1 study has evaluated the use of water-washable resins for crowns and fixed partial dentures.[37] More research is needed for AM appliances such as denture base resins, crowns, and fixed partial dentures, which require lower surface roughness, higher hardness, and a longer serving time in the oral cavity when new resins are introduced. The study's results also show that water-washable resins could be a good alternative to other AM devices, such as custom trays, trial denture bases, and surgical guides, where surface roughness and hardness are less important and which only stay in the mouth for a short time. A broader study should include ecofriendly AM approaches for different clinical applications.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. The interaction between the resin type and the postprocessing cleaning solution significantly affected the surface roughness of the 3D printed dental cast resins tested. Water-washable resin had similar surface roughness with all tested postprocessing cleaning solutions. Nonwater-washable resin had lower surface roughness with IPA or methyl ether solvent.
2. The interaction between the resin type and postprocessing cleaning solution significantly affected the microhardness of 3D printed dental cast resins assessed. Higher microhardness was obtained when nonwater-washable resin was post-processed with IPA or methyl ether solvent, and WW2 was postprocessed with IPA. WW2 had similar microhardness when water or methyl ether solvent was used, while WW1 specimens had microhardness similar to each other when cleaned with IPA or methyl ether solvent.
3. WW2 cleaned with water or methyl ether solvent resulted in surface roughness and microhardness comparable to when nonwater-washable (NWW) resin was rinsed with IPA; therefore, water or methyl ether solvent cleaned WW2 can be used for more ecologically friendly and sustainable dental cast fabrication without compromising the surface roughness and hardness of the casts.

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