Accepted: 18 February 2018
DOI: 10.1111/joor.12621

ORIGINAL ARTICLE

WILEY Journal of Oral Rehabilitation

Influence of CAD/CAM fabrication on denture surface properties

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Funding information
The present study is an academic study. It was carried out without funding. All costs were covered by the University Hospital for Dental Prosthetics and Restorative Dentistry of the Medical University of Innsbruck, Austria.

Summary

Three main properties are responsible for the microbial attractiveness of denture surfaces: roughness, hydrophilicity and free surface energy. This study investigated whether CAD/CAM-fabricated dentures are more favourable for these surface properties than conventionally fabricated dentures. The mucosal surface roughness of 54 standardised study dentures was measured using contact profilometry. The surface hydrophilicity and free surface energy of 70 standardised denture resin specimens were determined by contact angle measurements. Both experimental settings compared AvaDent (AD), Baltic Denture System (BDS), Vita VIONIC (VV), Whole You Nexteeth (WN) and Wieland Digital Dentures (WDD) surfaces with conventionally manufactured denture surfaces (control group). These data were analysed using ANOVA together with Tukey's test or the Games-Howell post hoc test. All CAD/CAM dentures had lower mean surface roughness values than conventional dentures. For AD, VV, WN and WDD, the differences were statistically significant. Vita VIONIC ($P < .001$), coated WN ($P < .001$), AD ($P = .023$) and BDS specimens ($P = .027$) were significantly more hydrophilic than the control group. All measured surface energies were of similar magnitude (mean values between 31.82 and 33.68 mJ/m^2), and only coated WN specimens had a significantly increased mean value (66.62 mJ/m^2, $P < .001$). Although most CAD/CAM dentures have smoother and more hydrophilic surfaces than conventional dentures, there is no difference in their free surface energy, except for coated dentures.

KEYWORDS
biofilms, complete denture, computer-aided design, oral hygiene, surface hydrophilicity, surface roughness

1 | INTRODUCTION

Micro-organisms colonising dentures have been linked to not only local mucosal inflammation,[1] caries and periodontitis of residual teeth[2] but also disseminated infections. Aspirated denture plaque has been shown to cause pneumonia[3] and can therefore be a severe health threat for patients with decreased immunity.[4] Among the many possible physical and chemical surface properties influencing microbial attachment to surfaces, surface roughness,[1,5-7] hydrophilicity[1,7-10] and free surface energy[6,11] seem to be most relevant. Rough[1,5-7] and hydrophobic[1,7-10] surfaces, as well as surfaces with a high amount of free surface energy,[6,11] promote strong microbial attachment and therefore increase the expenditure necessary for biofilm removal.[7] In addition, surface roughness and hydrophobicity influence the biofilm composition.[1,12] It was suggested that modulating the denture surface may be a promising target for facilitating denture cleanliness.[6,13]

Currently, most dentures are made from polymethyl methacrylate (PMMA)-based resins. Because PMMA contains a large number of carboxylate and methyl ester groups, it is hydrophilic and has a high amount of free surface energy.[8] However, denture base materials do not consist of pure PMMA. Rather, they contain a plethora of additives, such as polymerisation initiators, accelerators, cross-linking agents, fillers and colourants, each of them influencing not only the material's physical properties but also the chemical properties. A study comparing the free surface energy and wettability of different denture base materials showed significant variations regarding these surface features,[14] and the differences were attributed mainly to the additives.

Although the chemical composition seems to play a major role in determining the resin's chemical surface properties, the processing protocol is the main determinant of surface roughness. Gaseous porosities, caused by monomer vaporising at processing temperatures of 100.8°C or higher,[15] can cause surface irregularities. Although these irregularities can be countered by applying packing pressure,[16] the amount of applicable pressure is limited in conventional denture manufacturing, as too high pressure may cause fractures of the mould or the flask.[17] By contrast, in CAD/CAM denture manufacturing, the denture bases are milled from industrially polymerised resin pucks, and it is predicted that the resin in these pucks is highly condensed because of the high pressure the manufacturers apply during polymerisation.[18] Therefore, they are likely less porous and have a higher degree of polymerisation. In addition, the fully automated milling process should produce smoother denture surfaces than the conventional manual fabrication process.

The aim of this study was to investigate whether CAD/CAM-fabricated dentures are more favourable for surface roughness, hydrophilicity and free surface energy than conventionally fabricated dentures by testing 3 null hypotheses. The first null hypothesis was that mucosa-sided CAD/CAM denture surfaces do not have a different surface roughness than mucosa-sided conventional denture surfaces. The second null hypothesis was that CAD/CAM denture resins do not have a different hydrophilicity than conventional denture resins, and the third null hypothesis was that CAD/CAM denture resins do not have a different free surface energy than conventional denture resins.

2 | METHODS

2.1 | Surface roughness measurements

For the surface roughness measurements, a total of 54 dentures were analysed: 44 CAD/CAM dentures (study groups 1-5) and 10 conventional dentures (control group). The CAD/CAM dentures for the study groups were fabricated by the following leading manufacturers (in alphabetical order): AvaDent Digital Dentures (AD; Global Dental Science Europe BV, Tilburg, the Netherlands), Baltic Denture System (BDS; Merz Dental GmbH, Lütjenburg, Germany), Vita VIONIC (VV; Vita Zahnfabrik, Bad Säckingen, Germany), Whole You Nexteeth (WN; Whole You Inc., San Jose, USA), Wieland Digital Dentures (WDD; Wieland Dental + Technik GmbH & Co. KG, Pforzheim, Germany / Ivoclar Vivadent AG, Schaan, Liechtenstein). Each study group consisted of 10 CAD/CAM dentures, fabricated from 10 master casts of different anatomical configurations, except for group 3 (VV), which contained only 4 dentures. The conventional dentures were made from heat-polymerising resin (Candulor Aesthetic Red; Candulor AG, Glattpark, Germany) using the compressed mould technique and following a long-term heat polymerisation cycle (75°C water bath for 8.5 hours). The moulds were made from class IV gypsum (SheraPure; SHERA Werkstoff-Technologie GmbH & Co. KG, Lemförde, Germany) and isolated with plaster-against-resin separating fluid (Separating Fluid; Ivoclar Vivadent). All dentures were manually finished on the oral surfaces only. The mucosal surfaces were left unfinished, as is customary for clinical use.

The surface roughness was analysed using contact profilometry. The measurements were performed on the mucosal denture surfaces, perpendicular to the surface and the milling direction using a Form TalySurf Serie 2 FTS S2 contact profilometer (Taylor Hobson, Leicester, UK). The profilometer filter settings were chosen according to the respective ISO norm.[19] Five standardised profilometric measurements of 0.4 mm were performed on each denture. The cut-off wavelength was set at $\lambda = 0.08$ mm, and the surface roughness characteristics R_a, R_q, R_t and R_z were determined.

R_a (roughness average) is the most commonly used surface roughness characteristic. It is determined as the arithmetic mean of absolute values of the roughness profile ordinates. Roughness peaks larger than the defined cut-off value (λ) do not contribute to the measurement. R_q (root mean square roughness) is the root mean square average of the roughness profile ordinates. It is less sensitive to extreme values. R_t (roughness depth) represents the maximal peak-to-valley height in the measured profile, and R_z is the mean roughness depth, calculated as the average of all peak-to-valley heights over a defined number of evaluation lengths. R_z is more sensitive to changes in surface structure than R_a.

In addition to the surface roughness characteristics, CAD/CAM dentures showed a periodic surface profile (waviness) originating from the milling process (Figure 1). The milling groove configuration is described by the mean milling groove width (R_{sm}-value). Because the expected measuring level for R_{sm} was considerably higher than the surface roughness, the profilometry protocol was adapted to 1 continuous measuring distance of 15.1 mm and a cut-off wavelength of $\lambda = 0.8$ mm.

2.2 | Hydrophilicity and free surface energy measurements

To determine the hydrophilicity and free surface energy, rectangular denture base resin specimens sized 39 × 8 × 4 mm were used.

A total of 70 samples, divided into 6 study groups [1-6] and 1 control group, were analysed (Figure 2). Each group consisted of 10

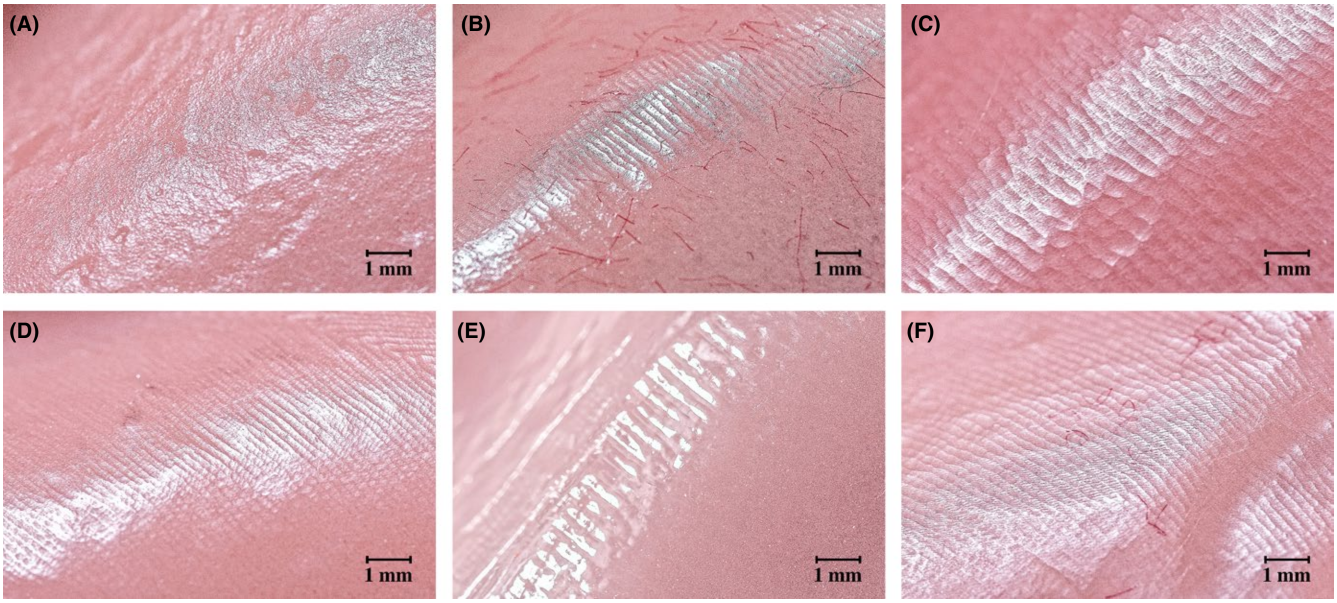

FIGURE 1 Enlarged images of mucosal denture surfaces. A, Conventional denture, B: AvaDent, C: Baltic Denture System, D: Vita VIONIC, E: Whole You Nexteeth, F: Wieland Digital Dentures [Colour figure can be viewed at wileyonlinelibrary.com]

specimens. Study groups 1-4 were provided by AD, BDS, VV, and WDD. Groups 5 and 6 were both provided by WN. Because WN dentures are always delivered with a full surface coating, the manufacturer was asked to provide 10 specimens with coating (WN_c, group 5) and 10 specimens without coating (WN_u, group 6). All CAD/CAM specimens were milled from CAD/CAM denture pucks. The 10 "conventional" samples for the control group were made from the same heat-polymerising resin following the same polymerisation protocol as the conventional dentures. All specimen surfaces were left unfinished, as is customary for the mucosa-sided denture surface. Prior to analysis, the resin specimens were stored in 100 mL of deionized water for 7 days at a temperature of 21°C in darkness to simulate the intraoral situation. After the storage period, each sample was removed from the container with forceps to avoid surface contamination, and the specimens were towel-dried with a paper tissue for 1 minute.

The hydrophilicity was assessed by measuring the water contact angle. For this purpose, deionised water droplets were automatically applied, and the droplet surface angle was automatically measured by the Drop Shape Analysis System 10 MK2 contact angle measurement system (Krüss GmbH, Hamburg, Germany). A small water contact angle indicated a high degree of surface hydrophilicity.

To determine the free surface energy, additional contact angle measurements were performed with droplets of 99.7% toluol and ethylenglycol puris p.a. The free surface energy was then calculated using the Drop Shape Analysis 1.51 Software contact angle measurement system (Krüss GmbH).

2.3 | Statistics

These data were analysed using IBM SPSS Statistics 22 (IBM, Armonk, NY, USA) and R 3.3.1 (R Foundation for Statistical Computing, Vienna, Austria). Continuous measures were described as mean values and standard deviations. These data were plotted in box plots and inspected for outliers. A Shapiro-Wilk's test and QQ-plot-inspection were used to test the data's normal distribution. To determine whether there were statistically significant differences between the study groups and the control group, 1-way ANOVA was performed in conjunction with Tukey's test or Games-Howell post hoc analysis. The homogeneity of variances was assessed by Levene's test for all groups. The significance level for statistical tests was set at $\alpha = .05$, and $\alpha = .01$ was set as the level for high statistical significance.

At the beginning of the study, sample size estimation was performed. Using 1-way ANOVA for comparison of the mean values of 6 groups of specimens, an effect size of Cohen's $f = 0.5$ between the variables of interest was considered relevant. To achieve a statistical power of 0.80 for discovering existing differences as statistically significant at a significance level of $\alpha = .05$, the calculated minimal sample size was n = 10 for each group.

3 | RESULTS

3.1 | Surface roughness

All CAD/CAM dentures had lower mean surface roughness values than conventional dentures (Table 1). All roughness values were highly significantly lower in WN dentures than in the control group ($P < .001$). R_a and R_q were highly significantly lower in AD dentures than in the control group ($P < .001$); R_t ($P = .042$) and R_z ($P = .012$) were significantly lower than in the control group. Wieland Digital Dentures dentures had highly significantly lower R_a, R_q and R_z values than the control group ($P_{Ra} < .001$, $P_{Rq} = .004$, and $P_{Rz} = .009$, respectively). Vita VIONIC dentures showed highly significantly lower

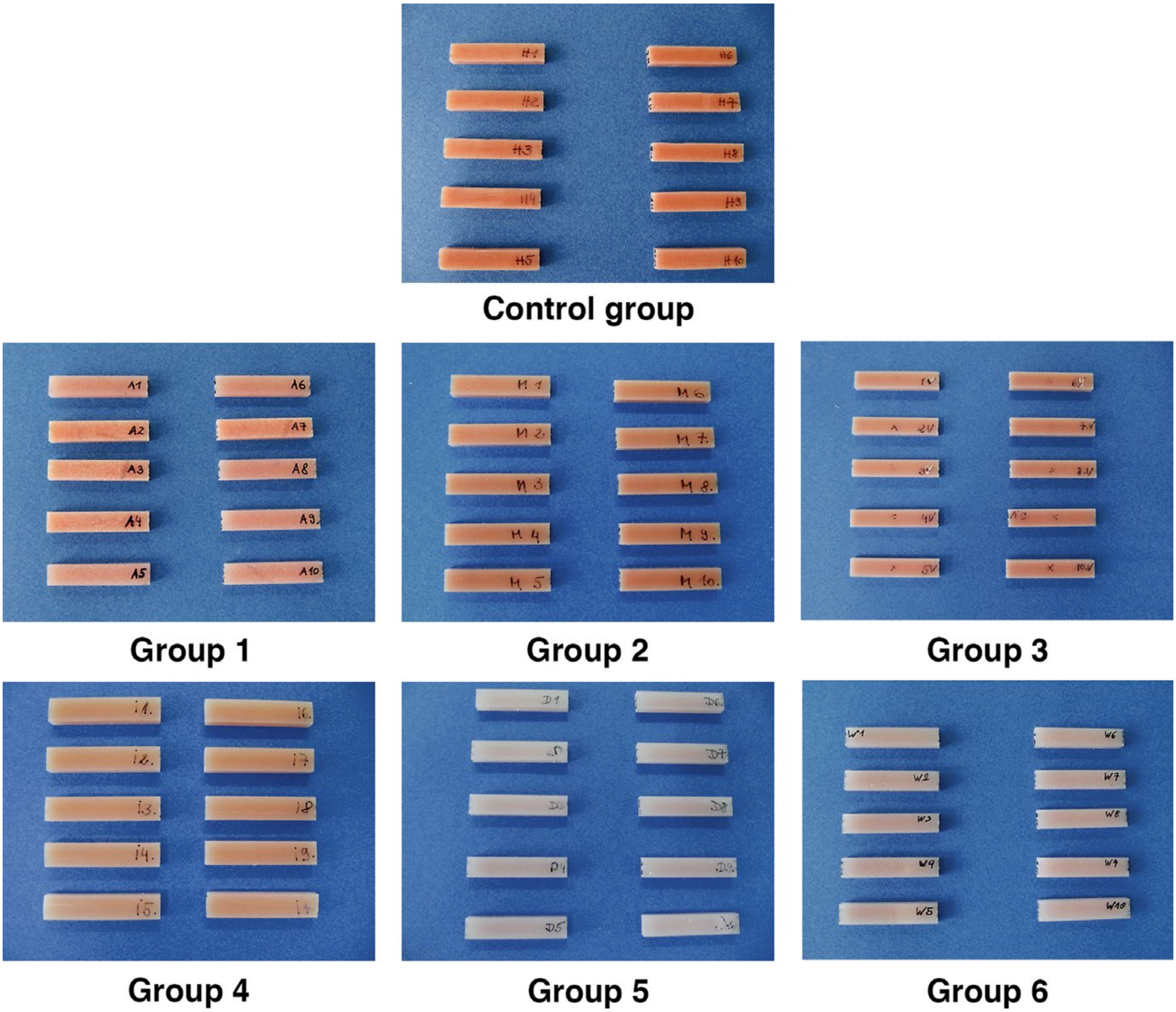

FIGURE 2 Specimens for contact angle measurements (hydrophilicity and free surface energy). Group 1: AvaDent, Group 2: Baltic Denture System, Group 3: Vita VIONIC, Group 4: Wieland Digital Dentures. Group 5: Whole You Nexteeth with coating, Group 6: Whole You Nexteeth uncoated, Control group: Candulor Aesthetic Red (heat-polymerising resin) [Colour figure can be viewed at wileyonlinelibrary.com]

R_a and significantly lower R_q and R_z values than the control group (P_{Ra} = .004, P_{Rq} = .012, P_{Rz} = .016). The R_t values of WDD (*P* = .106) and VV dentures (*P* = .053) were lower than those of conventional dentures, but the difference was not significant.

3.2 | Milling groove configurations

Vita VIONIC, WDD and AD dentures had similarly narrow milling grooves (mean R_{sm}-value for VV: 259.25 µm, SD = 29.85; mean R_{sm}-value for WDD: 288.40 µm, SD = 39.85; mean R_{sm}-value for AD: 298.90 µm, SD = 60.73). The milling grooves of BDS prostheses and of WN dentures were considerably wider (mean R_{sm}-values of 365.60 µm, SD = 89.76 for BDS and mean R_{sm}-values of 524.67 µm, SD = 63.63 for WN). The results are shown in Figure 3.

3.3 | Hydrophilicity

The mean values for the water contact angles varied between 26.50° (coated WN specimens) and 82.50° (heat-polymerised resin samples). Table 2 gives an overview of the water contact angles of the conventionally and CAD/CAM-processed specimens. The WN_c specimens had the most hydrophilic surface, and the difference compared to conventional, heat-polymerised resin was highly significant (*P* < .001). Vita VIONIC prostheses were highly significantly more hydrophilic than conventional dentures (*P* < .001). AvaDent (*P* = .023) and BDS (*P* = .027) specimens had significantly more hydrophilic surfaces than the heat-polymerised resin specimens. WN_u and WDD specimens were also more hydrophilic than the heat-polymerised resin, but the difference was not significant.

TABLE 1 Surface roughness parameters of conventionally and CAD/CAM-manufactured dentures

	n per group	R_a (µm) Mean (SD)	R_q (µm) Mean (SD)	R_t (µm) Mean (SD)	R_z (µm) Mean (SD)
Conventional dentures	10	0.55 (0.14)	0.69 (0.17)	3.49 (0.63)	2.35 (0.56)
AvaDent	10	0.28 (0.16)**	0.38 (0.20)**	2.24 (1.00)*	1.27 (0.67)*
Baltic Denture System	10	0.44 (0.13)	0.59 (0.19)	3.44 (1.13)	2.02 (0.67)
Vita VIONIC	4	0.28 (0.07)**	0.36 (0.10)*	2.01 (0.62)	1.26 (0.36)*
Whole You Nexteeth	10	0.04 (0.01)**	0.06 (0.03)**	0.32 (0.07)**	0.17 (0.04)**
Wieland Digital Dentures	10	0.30 (0.10)**	0.41 (0.16)**	2.39 (1.05)	1.39 (0.51)**

SD, standard deviation.
*Statistically significant difference compared to heat-polymerised conventional dentures ($P < .05$).
**Statistically highly significant difference compared to heat-polymerised conventional dentures ($P < .01$).

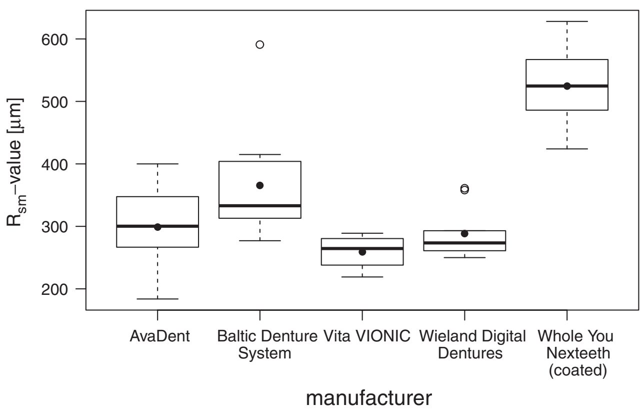

FIGURE 3 Boxplots of milling groove widths in different CAD/CAM denture systems

3.4 | Free surface energy

The surface energies of all specimens were of similar magnitude (mean values between 31.82 and 33.68 mJ/m^2, Table 2), except for the WN$_c$ specimens, for which the free surface energy was approximately twice as high (mean value, 66.62 mJ/m^2). The difference compared to the control group was highly significant ($P < .001$).

4 | DISCUSSION

4.1 | Experimental set-up

The aim of this study was to evaluate the surface properties of CAD/CAM-manufactured dentures that are relevant for primary microbial adhesion. For this purpose, the denture surface roughness, denture resin hydrophilicity and free surface energy were measured and compared to the values of conventionally manufactured dentures. The sample size was chosen according to the results of a statistical sample size estimation. Only the VV denture group showed a deviant sample size because the manufacturer could not provide more dentures at the time of the study.

To realistically represent the clinical situation, patient-based complete dentures were used for the surface roughness measurements. It is common practice to leave the mucosal denture surface unpolished to ensure maximal correspondence of the denture with the denture-bearing tissues. The quality and roughness of the mucosal denture surface is therefore determined by the resin quality and, more importantly, by the quality of the CAD/CAM milling burrs, or in case of conventional dentures, by the quality of the master cast and manufacturing protocol. Each CAD/CAM system uses different milling machines, using different milling burrs with a defined cutting geometry and a limited radius of movement. The different performances of the varying burr types and burr action become apparent only on irregular surfaces, such as denture bases. All CAD/CAM dentures showed undulating ripples on the denture surface, which could be observed macroscopically (Figure 1). On flat surfaces, such milling ripples do not occur. In daily practice, dentures do not contain such flat surfaces. Therefore, the roughness measurement must be performed on patient-based dentures, and the performance of the measurements on standardised denture areas ensured the comparability of results.

Although the quality of the mucosal denture surface is process specific, the quality of the oral denture surface mainly depends on the manual finishing skills of the dental technician. Therefore, the oral denture surfaces were not considered.

Although patient-based study dentures may be the most appropriate specimens for determining the clinical denture surface roughness, liquid contact angle measurements require a flat specimen surface. This is why standardised rectangular resin specimens were used for assessing the surface hydrophilicity and free surface energy in this study. The examined surfaces represented the unpolished mucosal denture surface. Whole You Nexteeth dentures are always delivered with a full coating. This coating, however, is lost when the denture base must be ground, for example in the case of a traumatic ulcer. To determine which properties the resin exposed

TABLE 2 Water contact angle (hydrophilicity) and free surface energy of conventionally and CAD/CAM-processed resins

	n	Water contact angle (°) Mean (SD)	Surface energy (mJ/m²) Mean (SD)
Conventional, heat-polymerised resin	10	82.50 (3.44)	33.00 (0.97)
AvaDent	10	70.35 (8.99)*	32.89 (5.44)
Baltic Denture System	10	75.00 (5.42)*	33.68 (2.26)
Vita VIONIC	10	74.40 (2.32)**	33.07 (0.82)
Whole You Nexteeth (with coating)	10	26.50 (5.58)**	66.62 (3.02)**
Whole You Nexteeth (without coating)	10	77.70 (9.87)	32.86 (2.81)
Wieland Digital Dentures	10	77.50 (3.34)	31.82 (1.17)

SD, standard deviation.
*Statistically significant difference compared to conventional heat-polymerised resin ($P < .05$).
**Statistically highly significant difference compared to conventional heat-polymerised resin ($P < .01$).

by grinding would exhibit, we extended the hydrophilicity and free surface energy analysis to uncoated WN denture resin specimens.

4.2 | Surface roughness

Surface roughness is considered relevant for primary microbial adhesion.[7,20] Microbial adhesion is enhanced with increasing surface roughness between 0.1 and 0.4 μm.[7,20] Another study described a R_a-cut-off value of 0.2 μm.[21] Below this R_a-value, the surface roughness does not influence bacterial adhesion or colonisation.[21] Our own preliminary experiments showed that a standardised oral denture surface finishing protocol involving surface processing with sandpaper with an ascending grain size up to 2500 grid and final high lustre finishing produces very smooth resin surfaces with mean R_a-values of around approximately 0.03 μm. As previously mentioned, surface finishing and polishing are performed on the oral denture surfaces, but the mucosal denture surfaces are customarily left unfinished to ensure maximal correspondence of denture surface and denture-bearing tissues. In the present study, all CAD/CAM dentures had smoother surfaces than the control group. The difference was significant for all CAD/CAM dentures, except BDS. Therefore, the first null hypothesis was rejected, except for BDS, which also showed lower surface roughness parameters but without statistical significance. The R_a-values on the mucosal denture surfaces of AD and VV dentures were close to the microbial adhesion cut-off value of 0.2 μm. This low roughness may either be caused by the high degree of condensation in the resin pucks or from a very favourable milling burr surface design. Nevertheless, the findings in the VV group must be regarded with some caution, because the group consisted of only 4 specimens. The even smoother mucosal surfaces of WN dentures, by contrast, may be attributed to the dentures' surface coating.

4.3 | Milling groove configurations

The milling grooves observable on mucosa-sided CAD/CAM denture surfaces are an issue of concern regarding biofilm retention and cleanability. In the present study, we found that there were great differences in the milling groove configuration between dentures produced by different CAD/CAM denture systems. To evaluate the clinical impact of these findings, in-vivo studies will be necessary.

4.4 | Surface hydrophilicity and free surface energy

Surface hydrophilicity and free surface energy are relevant for microbial adhesion mainly on very smooth resin surfaces.[8] Hydrophilic surface properties reduce the adherence of hyphal Candida albicans[13] and of bacterial cells.[9] In addition to being hygiene relevant, surface hydrophilicity may play an important role in enhancing denture retention.[14,22-24] In the present study, all CAD/CAM denture resin samples, except for WDD and WN_u, were statistically significantly more hydrophilic than the heat-polymerised denture base resins. Therefore, the second null hypothesis was rejected for WN_c, AD, BDS and VV.

It may therefore be deduced that CAD/CAM dentures might be less susceptible to microbial adhesion than conventionally fabricated dentures.

For free surface energy, an important cut-off value is postulated as 50 mJ/m². Surfaces with free energy values below this threshold seem considerably less attractive for microbial adhesion.[11] However, it must be stated that in vivo glycoprotein pellicle formation is the precursor of microbial adhesion.[14] Although the acquired pellicle seems to reduce differences in material wettability[25] and free surface energy,[26] the pellicle's composition depends on the material on which it forms.[14] Through this interrelation, the material composition might indirectly influence microbial adhesion. The present study showed that the WN_c resin samples were the only samples with significantly higher free surface energy compared to conventional dentures. Therefore, the third null hypothesis was rejected for only the WN_c resin. The free surface energy of WN_c was greater than the suggested bacterial adhesion threshold of 50 mJ/m². As previously described, the free surface energy may play a more predominant role in microbial adhesion on very smooth surfaces. In the present study, WN dentures were not only the dentures with the highest free surface energy, but also those with the lowest roughness values. Our own clinical observations showed that patients wearing CAD/CAM-fabricated dentures do not only present themselves with less denture plaque and calculus, they also report that the dentures are easier to clean.

5 | CONCLUSION

Although most CAD/CAM dentures have smoother and more hydrophilic surfaces than conventional dentures, there is no difference regarding the free surface energy, except for coated dentures. These surface properties might make CAD/CAM denture surfaces less attractive for microbial colonisation.

ACKNOWLEDGMENTS

The authors thank Global Dental Science Europe BV, Merz Dental GmbH, VITA Zahnfabrik, Whole You Inc. and Wieland Dental + Technik GmbH & Co. KG / Ivocar Vivadent AG and for providing the study specimens for the present study free of charge. The supporting companies had no involvement in study design, in the collection, analysis and interpretation of data, in the writing of the report or in the decision to submit the article for publication.

The authors thank Theresa Makarczuk and Thomas Pitscheider (Swarovski, Wattens, Austria) for their help with performing the profilometric measurements. The authors thank Ralf Kollefrath and Silvan Benz (Colténe, Altstätten, Switzerland) for their help with performing the contact angle measurements.

CONFLICT OF INTEREST

Otto Steinmassl declares that he has no conflict of interest. Herbert Dumfahrt declares that he has no conflict of interest. Ingrid Grunert reports personal fees from Mitsui Chemicals, outside the submitted work. Patricia-Anca Steinmassl reports speaker's fees from Candulor AG, outside the submitted work.

DISCLAIMER

The respective manufacturers are listed in alphabetical order.

ETHICAL APPROVAL

This article does not contain any studies with human participants or animals performed by any of the authors. For this type of study, formal consent is not required.

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How to cite this article: Steinmassl O, Dumfahrt H, Grunert I, Steinmassl P-A. Influence of CAD/CAM fabrication on denture surface properties. *J Oral Rehabil*. 2018;45:406–413. https://doi.org/10.1111/joor.12621