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ORIGINAL ARTICLE

CAD/CAM milled removable complete dentures: an in vitro evaluation of trueness

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Abstract
Objectives This study aimed to compare the trueness of one type of CAD/CAM milled complete removable dental prostheses (CRDPs) with injection-molding and conventionally manufactured CRDPs.
Materials and methods Thirty-three CRDPs were fabricated by three different manufacturing techniques (group CAD/CAM (AvaDent™): $n = 11$; group injection molding (Ivocap™): $n = 11$; group flask-pack-press: $n = 11$) using a single master reference model and incubated in artificial saliva for 21 days. The trueness of the entire intaglio surface along with five specific regions of interest (vestibular-flange, palate, tuberosities, alveolar crest, and post-dam areas) was compared. Non-parametric tests were used with a level of significance set at $p < 0.05$.
Results At baseline, there was no difference in the trueness of the total intaglio surfaces between the groups. After incubation, only the conventional CRDPs showed a significant improvement in trueness of the entire intaglio surface ($p = 0.0044$), but improved trueness was confirmed for all three techniques in most individual regions of interest. The 80–20 % /2 median quantile of the CAD/CAM group demonstrated the highest variability of individual readings, probably due to the size of the milling instrument. However, for all three techniques, 80 % of all deviations of the complete intaglio surface after incubation in saliva were below 0.1 mm.
Conclusions In this in vitro study, the trueness of the intaglio surface of all three investigated techniques seems to remain within a clinically acceptable range. Additional research is warranted on material-related aspects, cost-effectiveness, clinical performance, patient-centered outcomes, as well as other CAD/CAM techniques for CRDP fabrication.
Clinical relevance The intaglio surface trueness is an essential aspect in the clinical performance of CRDPs.

Keywords CAD/CAM · Complete removable dental prosthesis · PMMA resin · Dental materials · Trueness · Injection-molding · Artificial saliva · Complete denture prosthesis

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Introduction

The introduction and evolution of computer-aided designing and manufacturing (CAD/CAM) technology in dentistry have greatly revolutionized treatment concepts and prostheses fabrication. Although this technology has been well established in fixed prosthodontics, it is still an emerging technique in the field of removable prosthodontics. Conventional complete removable dental prosthesis (CRDP) fabrication has been effective and reliable since their inception [1, 2]. However, the clinical protocols involved for the construction of a conventional CRDP may be cumbersome, time-consuming, and

difficult to undergo, especially for elderly edentates who are multi-morbid and/or live in institutions. The advent of modified clinical protocols, for digitally manufactured CRDPs, has greatly shortened the treatment time, patient visits, and a considerable reduction in laboratory cost. Added advantages of the digitally manufactured CRDPs include easy reproducibility and the existence of a permanent digital record for future use. This may be particularly helpful, when a CRDP is lost in a nursing home. Certain CAD/CAM protocols for CRDP manufacturing allow transferring chosen features of the existing prosthesis into the novel CRDP which may present a considerable advantage for denture adaptation in geriatric patients with reduced neuroplasticity.

Fabrication of CRDPs using the CAD/CAM technology had been first reported in the early 1990s; yet, only a few scientific publications describe the fabrication process using this technology [3–7]. Over the years, there have been considerable developments progressively improving the methods of data acquisition and prostheses fabrication [8–10]. CAD/CAM manufacturing of CRDPs can either be achieved by an additive (rapid prototyping) or by a subtractive (computerized numerical control milling) process. The latter seems to be the most frequently employed method, and a recently published report highlights the effectiveness of CRDPs fabricated with this method [11–13]. However, scientific evidence related to the emerging technique of CRDP fabrication in terms of effectiveness, accuracy of fabrication, patient perception, clinical feasibility, and biological compatibility is scarce [14].

Whether the accuracy of CAD/CAM milled CRDPs are comparable to conventionally manufactured ones has been dealt with in very few studies [11]. Therefore, the aim of this in vitro study was to evaluate the trueness of CAD/CAM milled CRDPs and compare it with CRDPs fabricated with conventional, well-established laboratory procedures like “flask, pack and press” and “injection-molding.” Therefore, the null hypothesis set for this in vitro study was that there is no difference between the trueness of the intaglio surfaces of CAD/CAM milled CRDPs and of those fabricated by conventional manufacturing methods such as flask-pack and press as well as injection-molding.

Materials and methods

This in vitro study was conducted in the University clinics of dental medicine, University of Geneva, Geneva, Switzerland. No patient-related records or elements were used in this study, and hence, no ethical committee approval was required. The mapping and difference analysis, of the scans, were performed at the Centre for dental medicine, University of Zurich, Zurich, Switzerland.

Master reference model

A completely edentulous maxillary plaster study model was duplicated and cast into a cobalt-chrome alloy after three reference pyramids had been added on three regions of the alveolar crest. This reference model served as the master model for the fabrication of the entire sets of complete denture specimens evaluated in this study.

Samples and study groups

Thirty-three CRDP samples were fabricated using the above-mentioned reference model, applying three fabrication techniques with 11 specimens per group.

Group 1: CAD/CAM milled CRDPs

Eleven CAD/CAM milled dentures were manufactured for this group (AvaDent™, Global Dental Science Europe BV, Tilburg, Netherlands). The reference master model was scanned using a 3D laboratory scanner (IScan D103i Bundle Scanner, Cendres + Métaux, C + M, Biel, Switzerland). It is a high-resolution optical scanner at a 6-μm precision according to Papaspyridakos et al. [15]. The manufacturer states a nominal point spacing of 6 to 8 μm, a repeatability of 10 μm, and an accuracy of 20 μm. The built-in software automatically aligns the different scan sets to each other. The 3D scan of the master model was saved in a *.stl-format. The latter were exported to Global Dental Science through the AvaDent™ Connect software. Upon receiving the scan data, the manufacturers imported the files into the AvaDent™ design software, where the anatomical landmarks are automatically detected and indicated. The denture was designed using the software by means of its digital algorithm without reference to an antagonistic arch. After approval of the design preview by the investigators, 11 CRDPs were milled from a specially crafted acrylic block produced under high pressure. The selected denture teeth were nano-filled composite resin teeth Candulor PhysioStar NFC+ (Candulor AG, Wangen, Switzerland) which were later resin bonded into the milled denture body.

Group 2: injection molded CRDPs

The CAD/CAM milled denture was used as reference for the manufacturing of injection molded CRDPs. Hence, on the master model, 11 complete dentures conforming to the exact arch, teeth, and occlusal plane were fabricated by one master dental technician in a commercial dental laboratory. The set-up of these dentures was performed by means of a vestibular silicone key; hence, the shape and the thickness of the palatal plates were not necessarily identical. The injection molding technique (IvocapTM technique, Ivoclar Vivadent AG, Schaan, Liechtenstein) employed a modified polymethylmethacrylate

(PMMA) resin (Ivobase High Impact, Ivoclar Vivadent AG, Schaan, Lichtenstein).

Group 3: conventional CRDPs

Eleven CRDPs, similar to groups 1 and 2 in all aspects except for the manufacturing technique, were manufactured directly on the reference model using conventional PMMA resin (Ivoclar ProBase, Ivoclar Vivadent AG, Lichtenstein). Again, a vestibular silicone key was employed for the setup of the teeth. The technique employed was the conventional split-mold flask, pack and press technique. One very experienced dental technician manufactured these dentures in a university-based dental laboratory.

Artificial saliva

For immersion of the CRDP specimens, a custom-composed artificial saliva similar to the commercial product (Glandosane®, Helvepharm AG, Frauenfeld, Switzerland) was created [16, 17]. The composition of the artificial saliva used in this experiment is given below:

- 10.15 g/1 carboxymethylcellulose sodium (Fluka, Sigma-Aldrich Chemie, GmbH, Buchs, Switzerland).
- 30.45 g/l sorbitol (Calbiochem, Merck Millipore, Merck, KgaA, Darmstadt, Germany).
- 1.22 g/l potassium chloride (Merck, KgaA, Darmstadt, Germany).
- 0.856 g/l sodium chloride (Merck, KgaA, Darmstadt, Germany).
- 0.456 g/l di-kaliumhydrogenphosphate 3-hydrate (Merck, KgaA, Darmstadt, Germany).
- 0.148 g/l calcium chloride dihydrate (Merck, KgaA, Darmstadt, Germany).
- 0.052 g/l magnesium chloride hexahydrate (Merck, KgaA, Darmstadt, Germany).

Protocol

After 33 samples were fabricated, the intaglio/fit surfaces of the 33 specimens were scanned (IScan D103i Bundle Scanner, Cendres + Métaux, C + M, Biel, Switzerland), and the scan-data were saved in the prescribed digital format (*.stl format). Scanning was performed after a minimum time lapse of 7 days after processing. The clamp provided by the manufacturer of the Laboratory Scanner was used to hold the dentures in place during the scanning process. After scanning, all CRDPs were immersed in the above-mentioned artificial saliva solution at room temperature for a period of 21 days, when the intaglio surfaces of the dentures were scanned again. The scanning process resulted in one data set for the reference model and 66 data sets for the denture specimen (2 sets of 11 datasets for each group: pre- and post-saliva immersion). The corresponding surfaces of the reference model and the 3D images of the dentures were super-imposed using a 3D-software (Oracheck version 2.10, Cyfex, Switzerland) as shown in Fig. 1 with the pyramids excluded. After superimposition, five specific regions of interest (vestibular-flange, palate, tuberosities, alveolar crest, and post-dam) were defined (Fig. 2). The software measured the distances between the intaglio surfaces of the superimposed denture against the scanned master model [18].

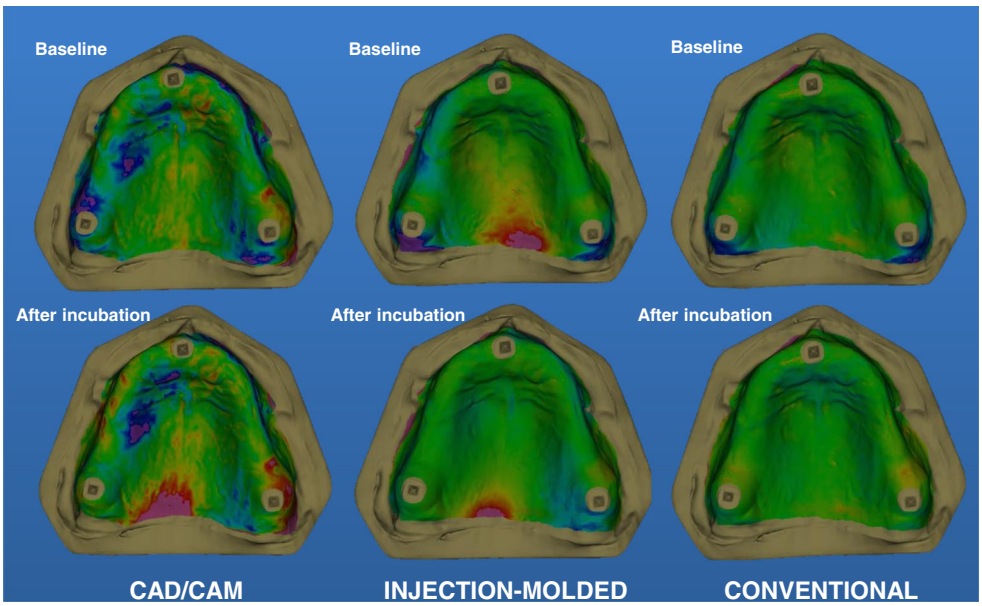

Fig. 1 Example of a color map of a specimen from each of the tested groups showing before (baseline) and after incubation in artificial saliva

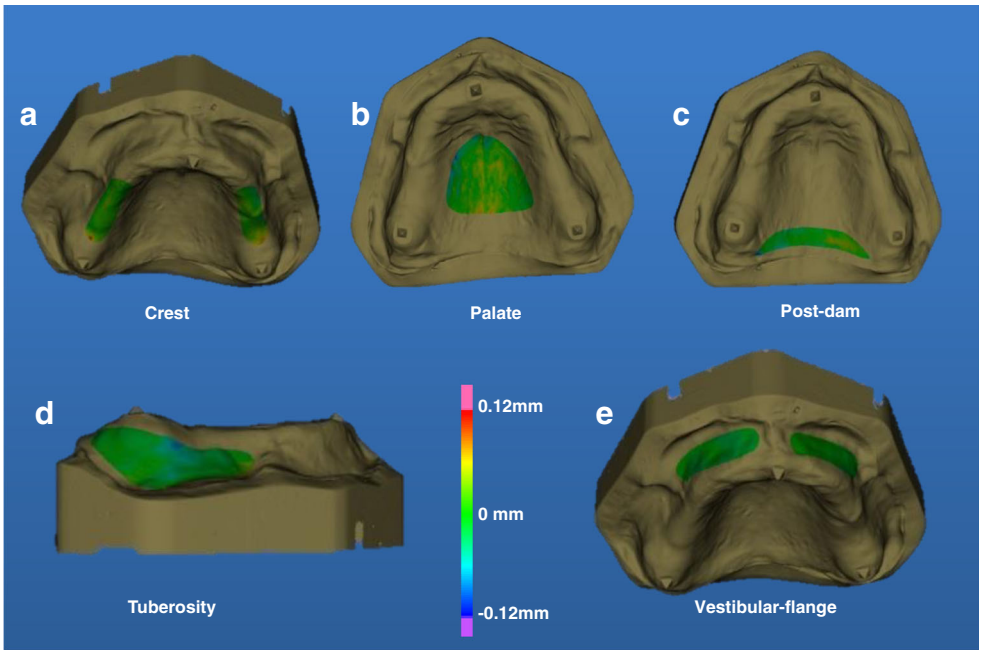

Fig. 2 Regions of interests analyzed shown on the scan of the master model

Statistical analysis

Wilcoxon's signed rank test was used to evaluate the effect of artificial saliva incubation on the trueness of the intaglio surfaces of the specimens, between the study groups and for the regions of interest within the study groups. The confidence interval (CI) was set at 95 % and level of statistical significance set to $p < 0.05$. Mann-Whitney test was used for an inter-group comparison of the trueness split by the regions of interests studied. Mann-Whitney tests were further used for evaluation of the potential denture "sore spots" (20 % quantile) and the "variability" of the individual trueness measurements (80–20 % quantile/2). The level of statistical significance was set to $p < 0.05$. Power analysis for sample size calculation was not done in this study as similar studies employed a minimum of 5 and a maximum of 10 samples per group. The current study employed a sample size of 11 specimens per group. Statistical analysis was performed by StatView version 5.0 statistical software package (SAS Institute Inc., Cary, North Carolina, USA).

Post hoc experiments

Scanning

After a preliminary analysis of the scans from the original protocol, a region of misfit beyond 0.1 mm (red color) was observed in the post-dam region adjacent to the screw of the scanner's scanning table in some of the CAD/CAM and the injection-molded specimens, but not in the conventional CRDP group. Hence, a rescan of all the CRDPs from all groups was done without the use of the screw of scanning table. By that time, the specimens had been stored dry for a period of 90 days. This time, the specimens were held in place by a scanning ring with 3 pins, and the dentures were fixated by means of sticky wax to ensure that no pressure was applied on the specimen.

Thickness of the post-dam

The thickness of the palatal plate in the post-dam area was measured for all the specimens. A characteristic landmark

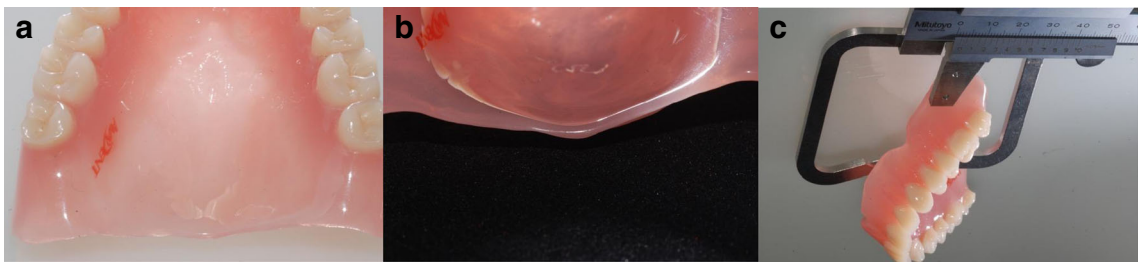

Fig. 3 Measurement of thickness of the fabricated complete removable dental prosthesis (CRDP) using a Gutowski's gauge (Mitutoyo, Classic dental Service, Taufkirchen, Germany). **a** Fabricated CRDP specimen from the CAD/CAM group, **b** midpoint of the post-dam area in the CRDP used for measurement, **c** using the Gutowski's gauge for measuring the CRDP thickness

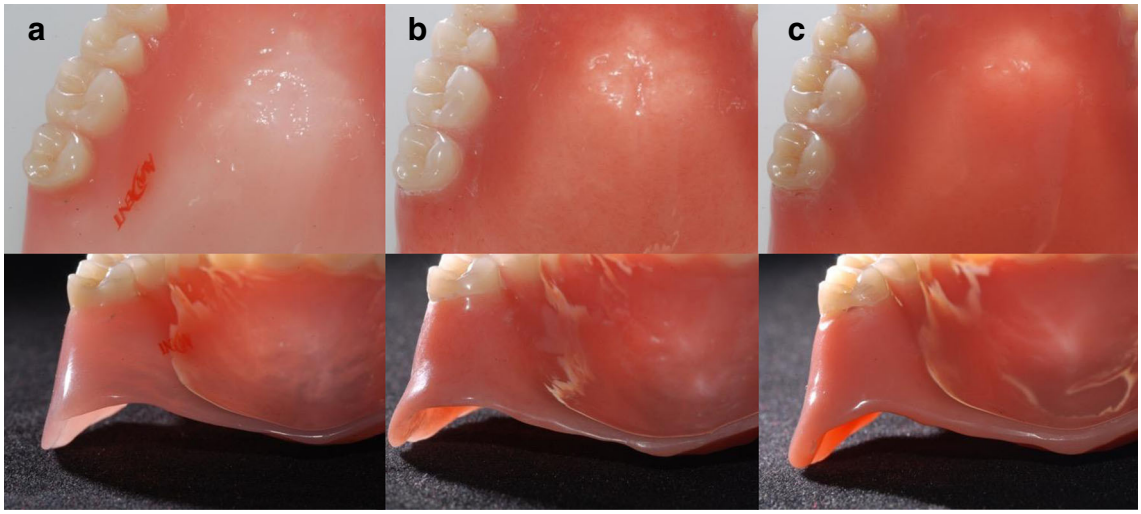

Fig. 4 Thickness of the fabricated complete removable denture prostheses in each of the tested groups, **a** CAD/CAM, **b** injection-molded, and **c** conventional

(mid-point of the post-dam area) was chosen to assure comparability between groups. Measurements were performed by a Gutowski-gauge (Mitutoyo, Classic Dental Service, Taufkirchen, Germany) (Fig. 3a–c).

Post hoc statistical analysis

Scans after 90 days were analyzed using the Oracheck software. Only the total surface scans (excluding the pyramids) were analyzed. Non-parametric Wilcoxon's signed-rank tests and Mann-Whitney tests were used to compare the trueness of this scan superimposed over the original reference model scan. Arithmetic means were calculated for the palatal thickness measurements. Data was checked for normal distribution using the Kolmogorov-Smirnov test. Standard paired *t*-tests were applied for analysis.

Results

Palatal thickness

When measuring, the palatal thickness of the conventional CRDPs showed the thickest palatal plate when compared to the CAD/CAM ($p < 0.0001$, paired *t*-tests) injection-molded ($p < 0.0001$, paired *t*-tests) groups. There was no difference between the CAD/CAM and the injection-molded groups (Fig. 4, Table 1).

Trueness of intaglio surface

At baseline, there was no significant difference (n.s.) in the trueness of the total intaglio surfaces of the CRDPs between the three groups. However, the variability of the median trueness of the individual measurement points was the lowest in the conventional group (CAD/CAM versus conventional $p = 0.0001$, injection versus conventional $p = 0.0007$, CAD/CAM versus injection n.s.; Mann-Whitney test).

After incubation in saliva, the conventional CRDPs showed a significant improvement in trueness of the entire intaglio surface ($p = 0.0044$) which was not present in the other two groups, despite a clear trend (Fig. 5, Table 2). However, the trueness of the CAD/CAM and injection CRDPs indicated equally an improvement, especially in the palatal and post-dam regions, where a clear misfit had been noted in the area of the clamp holding the denture in place during scanning (Fig. 6a–c, baseline and after incubation). For all three techniques, 80 % of all deviations of the complete intaglio surface after incubation in saliva are below 0.1 mm.

The improved trueness after incubation in saliva was confirmed for all three techniques, when considering only the

Table 1 Palatal thickness measurements and comparisons in the post-dam regions on the complete removable dental prostheses

Measurement	*CAD/CAM*	*INJECTION-MOLDED*	*CONVENTIONAL*
Mean ± standard deviation (in mm)	1.70 ± 0.06	1.81 ± 0.28	2.57 ± 0.20
Comparison	*p*-value (*t*-tests, significance at $p < 0.05$)		
CAD/CAM vs INJECTION	0.2490 (n.s.)		
INJECTION vs CONVENTIONAL	<0.0001		
CAD/CAM vs CONVENTIONAL	<0.0001		

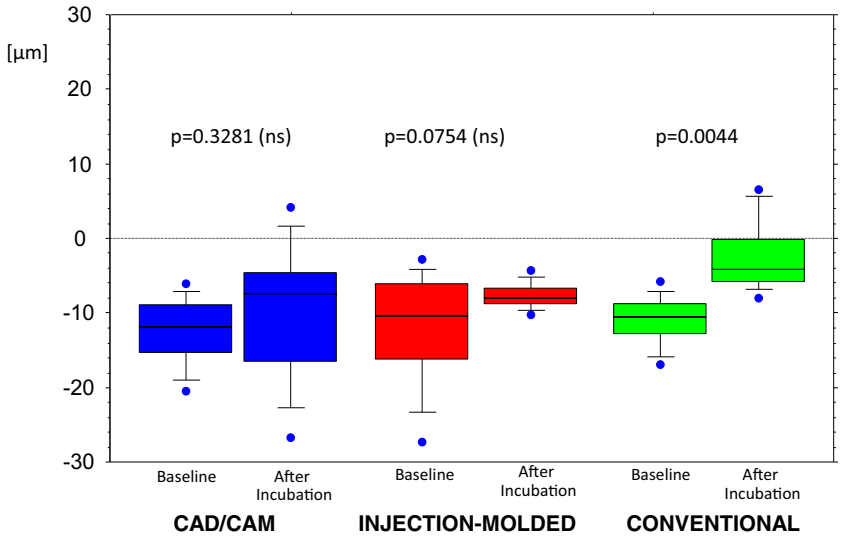

Fig. 5 Comparison of median (mean) values of the total intaglio surface within the groups before and after incubation in artificial saliva solution (*p* - value, Wilcoxon's signed rank test)

regions of interest. Incubation in saliva introduced a significantly better trueness in all regions of interest, except for conventional technique group in the post-dam and flange areas, as well as in the flange areas in the injection-molding technique group (Fig. 7, Table 2). Re-scanning of the intaglio surfaces after 3 months without clamping, but rather holding the CRDPs in the scanner by means of a sticky wax, reduced the misfit in the area around the palatal clamp, which had been noted during the baseline scanning and after the incubation in saliva (Fig. 6a, b). After 21 days of wet and 3 months of dry storage, a general "shrinkage" of the specimen was noted, demonstrating a significantly "tighter fit" for all three techniques (Table 2). Hence, the further analyses are only referring to the post-incubation measurements (Table 3).

Compression zones

The 20 % median quantile indicates the closest fit and may therefore be considered a "compression zone." With the exception of the tuberosities, CAD/CAM group showed the strongest compression when compared to the other two groups, especially in the vestibular flange area (Table 4, Fig. 8).

Variability of trueness

The 80–20 %/2 median quantile indicates the variability of the trueness readings from the individual measuring points of the intaglio surface. Here, the CAD/CAM group demonstrated the highest variability among the three groups, except for post-dam which was equally variable in the CAD/CAM and injection techniques (Table 5, Fig. 9).

Discussion

CRDP fabrication by CAD/CAM is a novel technology in removable prosthodontics, and no clinical trials concerning the denture fit are published till date. Scientific evidence related to the trueness of the intaglio surface and the material properties of the CAD/CAM milled CRDPs are scarce. Only one study has evaluated the accuracy of the denture bases manufactured by

Table 2 Intra-group comparison of trueness (baseline versus post-incubation in artificial saliva)

Regions of interest	*p* - value (Wilcoxon's signed rank test, confidence interval set at 95 %; split by manufacturing process and regions of interest; n.s.-not significant)		
	CAD/CAM	INJECTION	CONVENTIONAL
Crest	0.0099	0.003	0.0033
Palate	0.0033	0.0033	0.0033
Post-dam	0.0058	0.0099	0.8589 (n.s.)
Tuberosity	0.0033	0.0033	0.0033
Flange	0.0409	0.0912 (n.s.)	0.1307 (n.s.)
Total intaglio surface	0.3281 (n.s.)	0.0754 (n.s.)	0.0044
Total intaglio surface*	0.0044*	0.0058*	0.0058*

*Comparison of baseline versus 3 months without incubation

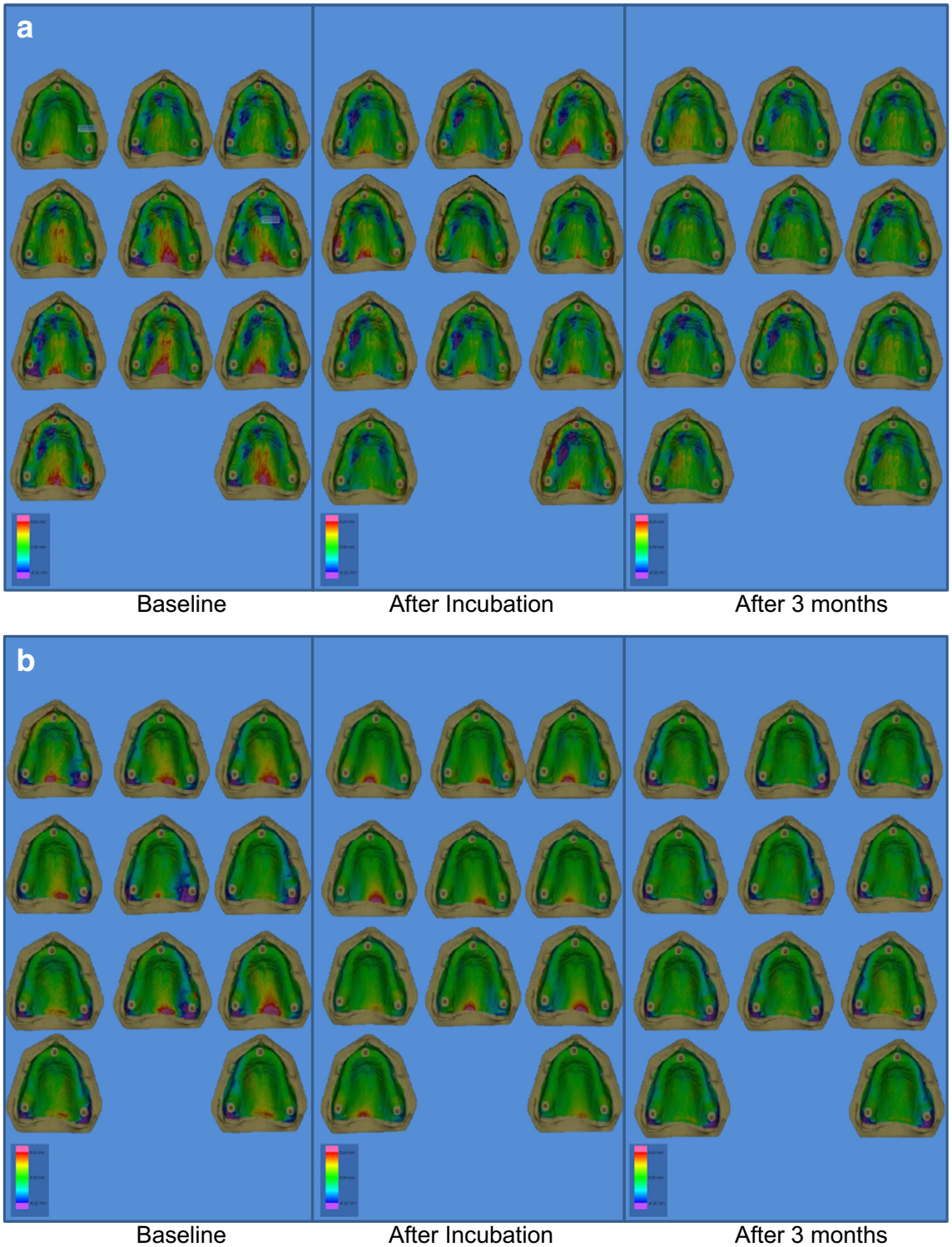

Fig. 6 **a** Color maps of all the specimens of the CAD/CAM group, **b** color maps of all the specimens of the injection-molding group, **c** color maps of all the specimens of the conventional group

different techniques as opposed to CAD/CAM milling [11]. Hence, the current study was undertaken as an attempt to evaluate the trueness of the CAD/CAM milled CRDPs by comparing it with CRDPs manufactured by traditional "flask, pack and press" and "injection-molding" methods. We wanted to confirm the validity of the novel CAD/CAM technique in bench experiments under standardized experimental conditions, before conducting a clinical trial.

The sample size adopted for the current bench experiments was in accordance with similar published studies involving

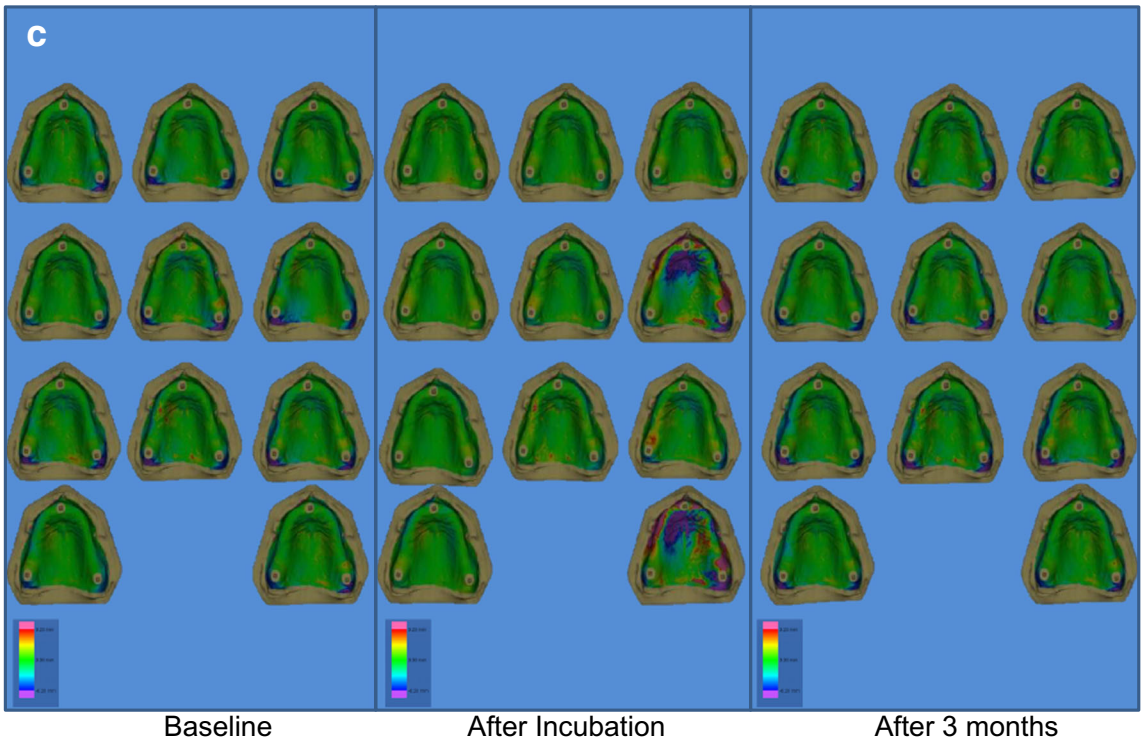

Fig. 6 (continued)

digital impression techniques, which recommend 10 scans from a single study cast per experimental group [19]. Goodacre and coworkers [11] used four experimental groups with a sample size of ten dentures per group in a similar bench experiment. In the current study, a sample size of 11 was chosen in order to respect the empirical rule of Harrell [20] and to avoid type II statistical errors [21].

The saliva substitute used and the incubation conditions deviated from a purely clinical context. Human saliva is a sophisticated exocrine secretion which follows a circadian rhythm, and the composition of saliva is dependent on this salivary flow rate [22]. The reproduction of the saliva's inorganic components is manageable; difficulty arises when trying to replicate the viscosity. The importance of using an appropriate liquid medium in bench experiments has been well-documented [23–25]. The artificial saliva substitute used for the current bench experiments was a previously described custom prepared solution similar to the commercially available Glandosane® [16, 17]. Furthermore, no thermo-cycling effect was mimicked in our experiments. Thermo-cycling is known to decrease the microhardness of the denture bases [26, 27].

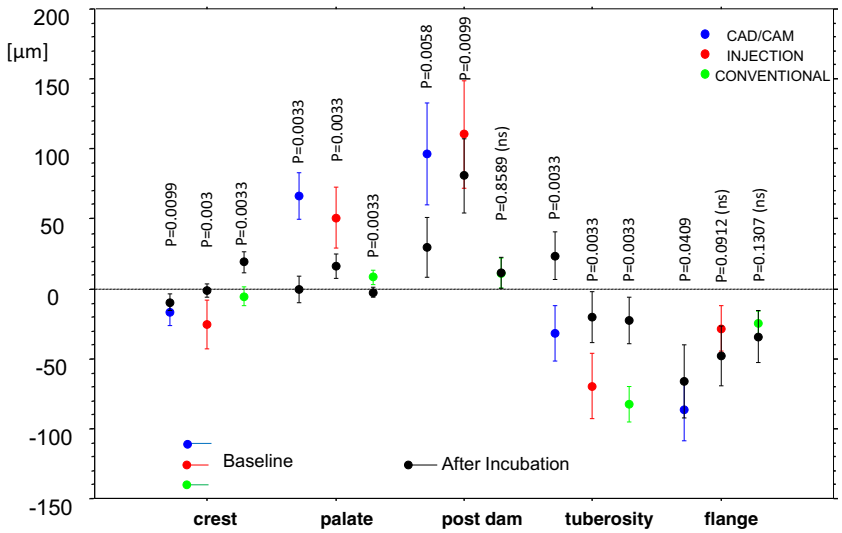

Fig. 7 Intra-group comparison of median (mean) values in the regions of interest at baseline and after incubation in artificial saliva solution (*p* value, Wilcoxon's signed rank test)

Table 3 Inter-group comparison of trueness (post-incubation in artificial saliva)

Group comparison	*p* - value (Mann-Whitney test, level of statistical significance set to $p < 0.05$; n.s.-not significant)					
	Crest	Palate	Post-dam	Tuberosity	Flange	Total intaglio surface
CAD/CAM vs INJECTION	0.4502 (n.s.)	0.0009	<0.0001	0.0002	0.1228(n.s.)	0.7180 (n.s.)
INJECTION vs CONVENTIONAL	0.0003	<0.0001	<0.0001	0.7180 (n.s.)	0.1077 (n.s.)	0.0014
CAD/CAM vs CONVENTIONAL	0.0078	0.6224 (n.s.)	0.0235	0.0001	0.0064	0.0278

Table 4 Inter-group comparison of the 20 % median quantile values indicating potential denture "sore spots"

Group comparison	*p* - value (Mann-Whitney test; level of significance set to $p < 0.05$; n.s.-not significant)				
	Crest	Palate	Post-dam	Tuberosity	Flange
CAD/CAM vs INJECTION	<0.0001	<0.0001	<0.0001	0.0386	<0.0001
INJECTION vs CONVENTIONAL	<0.0001	0.0012	0.0613 (n.s.)	0.5767 (n.s.)	0.0386
CAD/CAM vs CONVENTIONAL	<0.0001	<0.0001	<0.0001	0.0115	<0.0001

Scanning errors should also be considered. The high-quality laboratory scanner used is equipped with a fully automated calibration method which, to a large extent, is directly related to the temperature changes in the scanning compartment. Since the facility in Geneva is not climate controlled, the influence of the thermal changes may account for a source of error. A repeated recalibration ensured that the temperature cline would not be a factor affecting the accuracy of the scans. A further possible source of error which could have affected the scan accuracy may be due to the powder coating before scanning the model and the CRDPs. Schaefer et al. (2014) have reported that the powder coating may have a detrimental effect on the marginal fit and internal adaptation in partial coverage restorations; however, in the same report, they stated that the deviations still remained within clinically acceptable thresholds [28]. Enders and Mehl (2013) reported that digital impressions for complete-arch seem less accurate and demonstrate a different pattern of deviation than conventional impressions [29]. Although these issues may be of considerable relevance in fixed prosthodontics, inaccuracies in the range of micrometers are deemed clinically acceptable in complete denture prosthodontics, but this still needs to be scientifically proven.

In order to maintain standardization in the scanning process, a single investigator (YC) performed the digital scans of the master model, and the CRDPs. As mentioned above, during the scanning process, the clamps used to fix the dentures to the scan table might have been fastened rather tight causing an area of misfit around the palatal clamp which was visible in the scans of the CAD/CAM and injection molding CRDPs (Fig. 6a, b). The absence of this misfit in the conventional

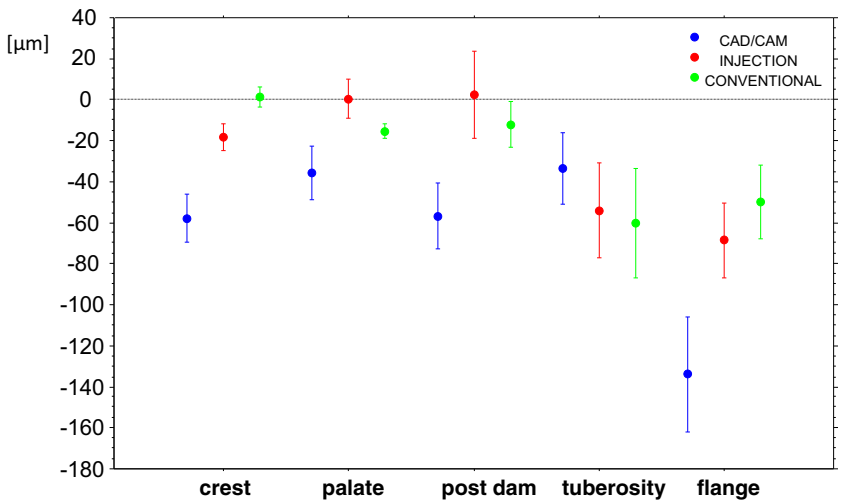

Fig. 8 Inter-group (post-incubation) comparison of the 20 % median quantiles indicating potential denture "sore spots"

Table 5 Inter-group comparison of the 80–20 % median quantile/2 values indicating "variability"

Group comparison	*p*-value (Mann-Whitney test; level of significance set to $p < 0.05$; n.s.-not significant)				
	Crest	Palate	Post-dam	Tuberosity	Flange
CAD/CAM vs INJECTION	<0.0001	0.0003	0.3088 (n.s.)	<0.0001	<0.0001
INJECTION vs CONVENTIONAL	0.3088 (n.s.)	0.0018	0.0001	0.7676 (n.s.)	0.2004 (n.s.)
CAD/CAM vs CONVENTIONAL	<0.0001	0.0012	<0.0001	0.0003	<0.0001

CRDP group, where the specimens presented with a thicker palatal plate, as well as the absence of this misfit in the 3-month post hoc scanning of the specimens strengthens the hypothesis of a mechanical distortion during clamping. The different thicknesses of the palatal plate in the three groups was unintentional and was only discovered after the experiments were completed. Giving precise instructions concerning the palatal thickness to the manufacturers of the CRDPs might be an important feature for similar future studies. However, the thinner CAD/CAM milled palatal plates might be an important factor in patient satisfaction, providing a more natural sensation and a more physiological tongue posture. It may also enhance thermal sensation during hot and cold food intake. The mechanical distortion noticed in our current experiment does not justify prescribing a thicker palatal palate. Firstly, forces due to clamping do not occur during normal denture wearing. Secondly, the misfit in the post-dam area due to clamping during scanning was not larger than 0.1 mm, a range that would at any rate be compensated by cutting a groove of 0.4 to 0.7 mm depth in the plaster cast in the post-dam area on the master model. However, further research needs to verify, if the claimed enhanced mechanical properties of the pre-polymerized PMMA resins allows such thin palatal plates without an increased incidence of denture fracture in a clinical situation.

In a conventional denture manufacturing technique, the procedures of mixing the resin, packing, flasking, as well as heat-polymerization are sources for inconsistencies, which result in a final distortion of the prosthesis. It is well established that PMMA resin incorporates water when immersed in a wet environment like the oral cavity. Also, the well-documented effect of linear shrinkage during processing usually results in a small spacing between the palatal mucosa and the denture's palatal plate [30–33]. The release of initial tensions from the polymerization process might further account for the reported changes in shape [34]. The initial misfit after processing, as well as the settling of the denture into the denture bearing tissues justify remounting the dentures after a period of 10–14 days after insertion. It is tempting to suggest that the enhanced density of pre-fabricated pucks in the CAD/CAM and the injection resin reduce water intake and thus reduce the volume changes introduced by the flask, pack, and press techniques. Milling the denture from a pre-polymerized block would create mechanical "milling tensions," but no polymerization tensions.

A difference in the fit of the total intaglio surface was noted between the three manufacturing methods only after incubation in saliva. The interpretation of current results mainly focuses on the post-immersion trueness of the intaglio surface, as we consider this the clinically most relevant finding. The better trueness of the overall intaglio surface of the conventional dentures may be explained by the many years of experience which the dental technician who manufactured the conventional dentures has. Given that he did not work in a private, hence not in a competitive environment, he took all the time

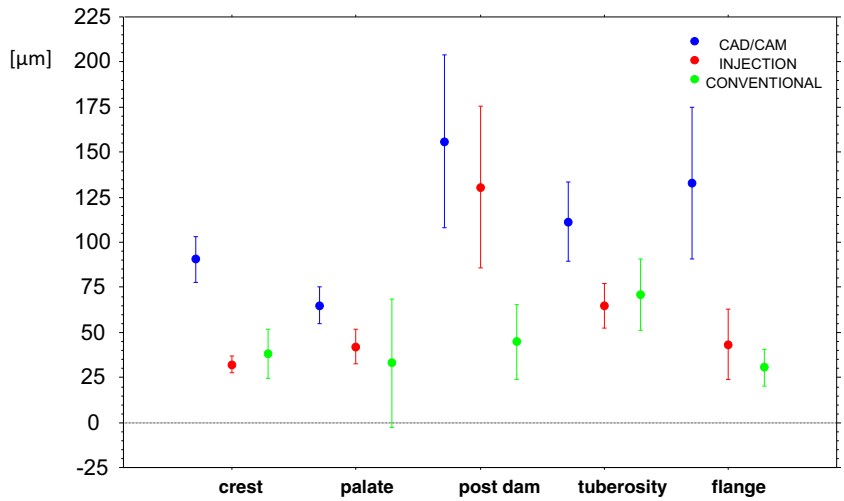

Fig. 9 Inter-group (post-incubation) comparison of the 80–20 % median quantile/2 values indicating "variability"

he needed to pack, process, and subsequently cool the flask. This might have minimized the post-polymerization tensions and distortion of the prostheses and explained the excellent adaptation of the palatal plate. However, when analyzing the individual regions of interest, CAD/CAM and injection techniques do equally show an overall improved trueness after immersion in saliva. When interpreting trueness, it has to be borne in mind, that a misfit with space from the master model resulted in a *positive* value (red color) and a compression of the tissues is indicated by *negative* values (blue color) (see Fig. 6a–c). Hence, calculating the mean value might have "neutralized" the spacing and compression zones. All fit surfaces corresponded with an accuracy of 0.1 mm to the originally scanned master model. Consequently, all the three CRDP groups provide adequate and clinically acceptable physical denture retention via cohesive and adhesive forces.

Interestingly, the CAD/CAM milled CRDPs presented the highest variability of trueness of the intaglio surface (Fig. 9). In fact, the 80–20 % quantile was more than twice as large for the CAD/CAM dentures as for the standard techniques. This can be explained by the size of the milling instrument which is inevitably larger than the particle size of stone plaster. The intaglio surface of a CAD/CAM milled denture is therefore not smooth, but rather "terraced," a phenomenon that can also be observed in the images from Goodacre et al. (2016). Inevitably, the size of the milling instrument determines the smoothness of the fit surface, but also the time which is needed to cut the denture base. A micro-terraced intaglio surface is not necessarily a clinical disadvantage, as it does not seem to compromise the overall fit of the denture. Micro-spaces for saliva might even contribute to the adhesive forces. On the other hand, the micro-roughness might increase the adhesion of biofilm and render denture cleaning difficult. Clinical studies will have to investigate the ideal balance between fit surface detail and manufacturing time and cost.

When investigating the different regions of interest, it can be noted that all three techniques seem to create some sort of compression in the vestibular flange area. This means that the scanned denture surface penetrates the scanned cobalt-chrome master model indicating a compression of the tissues when the denture is seated in the mouth. This may be due to its vertical position which makes it more vulnerable to distortion. For the CAD/CAM techniques, an increased imprecision might be added when vertical surfaces are scanned, as more surface of the alveolar ridge is represented in each single pixel. To minimize this source of imprecision, we scanned our reference model as well as the denture specimen from various angles. When interpreting these results, it further has to be considered that in the present experiments, an edentulous ridge was chosen without pronounced undercuts and with a shallow palate. Had the roof of the mouth or the tuberosities been steeper, the shrinkage during heat polymerization would have probably increased the misfit of the intaglio surface [34]. For these shapes of the alveolar ridge, a milled CRDP from a prepolymerized block may be considered more favorable and result in a better trueness in terms of adaptation of the palatal plate and tuberosities, but this hypothesis remains to be proven. Compression in the area of the vestibular flange was most prominent in the CAD/CAM group. In a clinical context, such compression might foster the denture adhesion and provide a tighter inner seal. The anterior inner seal is very vulnerable to the patient's movement during impression taking, and a lack of retention at insertion can often be related to such an "open inner seal," especially when silicone impression materials are used. During conventional impression taking a second layer of impression material is often used to achieve a slight compression and hence a tight inner seal. The CAD/CAM technique provided such a compression "automatically"; hence, this extra treatment step might not be necessary; however, this hypothesis remains to be confirmed by a clinical study. Our first clinical experiences with the CAD/CAM milled CRDPs confirm a very good retention, which might in fact be related to the compression of the inner seal. The reported median compression of 0.1 mm might present an ideal balance between a tight fit and painful injury, which can only be expected with compressions beyond 0.5 mm.

Conclusions

Based on the findings of this study, the null hypothesis can only be rejected for the post-saliva measurements, where CAD/CAM and injection molded CRDPs present a significantly lower trueness of the total intaglio surface than conventional CRDPs. However, measures in the present experiments are relative and a consistently superior technique cannot be determined, when individually analyzing certain regions of interest. Overall, the trueness of the intaglio surface of all three techniques investigated seems to remain within a clinically acceptable range. To further compare novel and conventional CRDP manufacturing techniques, additional research is warranted on material-related aspects, cost-effectiveness, clinical performance, patient-centered outcomes, as well as other CAD/CAM techniques for CRDP fabrication.

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Compliance with ethical standards

Conflict of interest Dr. Murali Srinivasan declares he has no conflict of interest related to this study. Yoann Cantin declares he has no conflict of interest related to this study. Prof. Albert Mehl declares he has no conflict of interest related to this study. Dr. Harald Gjengedal declares he has no conflict of interest related to this study. Prof. Frauke Müller declares she

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Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this in vitro study, a formal informed consent was not required.

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