JO JOURNAL OF OSSEOINTEGRATION periodontics and prosthodontics

The effect of two different milling instrument sets on CAD proposed cement thickness and fit surface of chairside CAD crowns

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TO CITE THIS ARTICLE
Skordou T, Kebi L, Osnes C, Keeling A. The effect of two different milling instrument sets on CAD proposed cement thickness and fit surface of chairside CAD crowns. J Osseointegr 2021;13(4):S271-S278.

DOI 10.23805/JO.2021.13.S04.3

KEYWORDS Digital dentistry; CAD/CAM crowns; Internal fit; Cement thickness; Milling instruments.

ABSTRACT

Aim To investigate the influence of milling instrument software presets on the proposed internal fit of anterior and posterior chairside fabricated CAD/CAM crowns.

Methods A total of 24 plastic upper right central incisors (#11) and 24 plastic lower left first molars (#36) were prepared by two practitioners and scanned with an Omnicam intraoral scanner (Dentsply Sirona Inc.). Crowns were designed with inLab CAD software (SW 19.0, Dentsply Sirona Inc.) for the MC XL milling machine. Two design strategies were used: Step Bur 12 with Cylinder Pointed Bur 12S (Group 12) and Step Bur 12S with Cylinder Pointed Bur 12S (Group 12S). The maximum, mean and standard deviation of the planned fitting surface (taking into account bur shape) for Group 12 and Group 12S were compared against the ideal fitting surface. Paired t-tests were used to assess statistical significance ($p<0.05$).

Results Group 12 performed significantly better ($p<0.001$), with proposals deviating less from the fitting surface, than group 12S for both anterior and posterior crowns. Group 12S showed the highest deviations in the designs proposed for the incisors, reporting maximum distances of 531 (±107) µm, where Group 12 reported 369 (±112) µm. The maximum distances for the molars were 326.91 (±65.53) µm for Group 12S as opposed to 245.41 (±49.18) µm for Group 12.

Conclusion Within the limitations of this study, bur set 12 produced crown proposals with less deviation in cement thickness than those for the 12S burs for upper central incisor and lower first molar crowns. Both methods showed deviations of >0.3 mm incisally, which might lead to thinner crowns and increased risk of fracture. When preparing teeth for milled chairside CADCAM crowns using an MC XL miller, a further occlusal/incisal reduction of up to 0.5 mm beyond manufacturers guidelines must be performed to ensure the correct crown thickness is maintained. Step Bur 12 should be used in preference to Step Bur 12S, to minimise, but not eliminate, this over-milling.

INTRODUCTION

CAD/CAM technologies are commonly used in dentistry to manufacture clinical restorations. It is generally accepted within the literature that CAD/CAM prostheses fabrication is less technique-sensitive than conventional methods, offering predictable treatment planning (1–3). Chairside manufacture offers time efficiency, and the popularity of single visit crowns encourages the use of fast milling machines and time-saving instrument options.

There are various confounding factors that influence the fit of CAD-CAM crowns such as scanner accuracy (4), design software accuracy (5), and design parameters (6). Milling accuracy can significantly affect the internal and marginal fit of crowns and potentially result in adverse clinical implications (5). An important question arises concerning the effect of bur diameter on the internal surface of CAD/CAM fabricated crowns, especially at the occlusal/incisal area, which is directly related to the final quality of internal fit and cement thickness. Current literature suggests that the milling bur diameter is crucial because large diameters result in voids caused by 'over-milling' the material (5, 6), while preparation edges that are smaller than the bur diameter are not milled correctly (7). However, the effect of different milling burs on these inaccuracies has not been adequately explored.

The internal and marginal resistance form of crowns depends on the uniform and minimal distribution of cement (8–10). Manufacturers generally propose an ideal material layer thickness to ensure retention and resistance form and thus clinical success (11). Poor occlusal fit can result in poor support of the material and unstable adhesion between the crown and the tooth (12). Further, the milling machine's ability to reproduce the proposed design may affect the cement space thickness and its uniform distribution, and consequently the crown

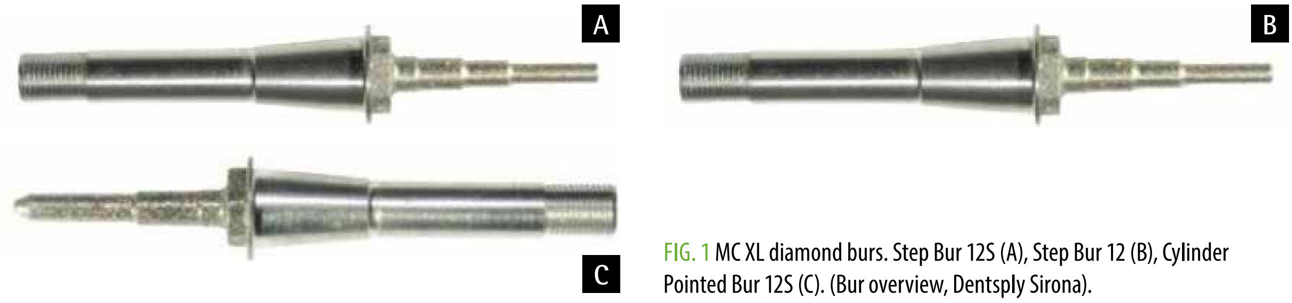

FIG. 1 MC XL diamond burs. Step Bur 12S (A), Step Bur 12 (B), Cylinder Pointed Bur 12S (C). (Bur overview, Dentsply Sirona).

fit and potential longevity (13). Rekow et al. (9) found that radial cracks might occur in the cement bulk when loads are applied, especially occlusally. Proper resistance form can positively affect stress distribution on cement and a uniform fit is crucial to avoid clinical failure (10). In addition to clinical failure, misfits may engender biofilm colonisation, cement dissolution, microleakage, recurrent caries, and gingival and periodontal issues (14).

The appropriate cement layer thickness is disputed, with recommendations ranging from 20-50 μm (9) to 50-100 μm as an acceptable range of internal fit (8,13); despite ISO (International Organisation of Standardisation) standards recommending 25 μm of maximum cement thickness for water-based materials (ISO 9917-1:2007) and 50 μm for resin-based cements (ISO No. 4049:2000). Perhaps of greater concern is the effect that increased cement space will have on the thickness of the crown material. For example, during incisal reduction the clinician will provide adequate occlusal clearance using manufacturers preparation guidelines. If the burs over-mill, the resulting crown will be thinner than planned, which may lead to early mechanical failure. The point of failure will be the thinnest part of the crown, and there is no literature on the scale of this potential problem.

The effect of CAD parameters on aspects such as spacer thickness and crown fit have not been sufficiently explored in the literature. Most research to date has evaluated the final fit and cement layer thickness of a crown, with limited investigation into how the nature of the CAD file itself may affect crown fit. It has been reported that CAM machines failed to replicate the designed cement space when manufacturing crowns (15), and thus having an awareness of the computer aided designed crown's impact on the final clinical fit could be advantageous, as it could be used to inform the clinician's decisions while designing the initial tooth preparation (12).

The Dentsply Sirona MC XL chairside milling unit uses a variety of bur sets according to the restoration's type, size and material. The burs differ in material and geometry; for example, carbide is used to mill zirconia and diamond to grind glass-ceramics. Zimmermann et al. (16) and Bosch et al. (17) confirmed that the result of the milling process is affected by the bur's diameter by testing different machines and milling methods, including MC XL.

The MC XL milling machine offers two main options for bur setups, a cylinder pointed bur 12S, which is used to mill the outer surface of restorations and an option between two step burs (12 or 12S) for the internal surface. Step bur 12 is 0.95 mm thick while step bur 12S 1.35 mm thick (Fig. 1). Both burs are 12 mm long.

The aim of this study was to digitally investigate the effect of two different bur sets (Group 12: Step Bur 12 with Cylinder Pointed Bur 12S. Group 12S: Step Bur 12S with Cylinder Pointed Bur 12S) on the quality of the fitting surface of anterior (central upper incisor) and posterior (lower first molar) crowns, with regard to the proposed maximum cement layer thickness of the final restoration. Unlike previous *in vitro* studies, the present study focused on the proposed cement layer thickness, focusing only on the digital data, to gain an insight into the influences decisions made in the CAD software may have on the final crown.

The null hypothesis of this study was that there would be no difference in maximum, mean or standard deviation distance values of proposed cement layer thickness between designs produced for bur set 12 and bur set 12S.

MATERIALS AND METHODS

Plastic teeth in model jaws (Frasaco, Germany) were prepared in phantom heads by two clinicians: 12 maxillary central incisors (#11) and 12 mandibular first molars (#36) were prepared by each clinician according to feldspathic crown preparation guidelines. The specimen preparations (n=24 for the central incisor and n=24 for the first molar) were quality assured by an additional experienced clinician, using 3.5x magnification loupes. The 48 prepared specimens were placed in separate PVS bases which were modified with grooves to facilitate scanning. The specimens were 3D scanned using CEREC Omnicam and Connect SW V4.6 (both Dentsply Sirona Inc.). The 48 preparation scans were exported as high resolution STL files.

Each preparation scan STL was imported into inLab design software (SW V19.0, Dentsply Sirona Inc.). "Biogeneric individual" mode was selected for the crown designs. The restoration parameters were adjusted manually, to Vita mark II (Vitablocs Mark II; Vita Zahnfabrik, Germany) material settings. The rest of the parameters were accepted as set by default (25 μm proximal, occlusal and

Group	Bur set	Radial spacer (μm)	Occlusal spacer (μm)	Min. radial material thickness (μm)	Min. occlusal material thickness (μm)	Consider instrument geometry	Consider instrument at margin	Remove undercuts
Gold Standard	-	0	0	1080	1580	-	-	-
Group 12	12	80	80	1000	1500	✓	✓	✓
Group 12S	12S	80	80	1000	1500	✓	✓	✓

TABLE 1 Parameter settings of each test group on inLab design software.

dynamic contact strength, 50 μm margin thickness, 50 μm width of ramp and 60 degrees angle of ramp). Three different groups of designs were exported in STL format. 24 files were designed as the Gold Standard. These designs would represent the actual tooth preparation, and help overcome alignment issues that would occur during measuring if the initial preparation scans were used. No spacing was added to these designs. The options of considering instrument geometry, considering instrument at margin and removing undercuts were not selected for the gold standard group in order to successfully replicate the tooth preparation surface. Two additional groups were designed using the two different bur sets (Group 12: Step Bur 12 with Cylinder Pointed Bur 12S. Group 12S: Step Bur 12S with Cylinder Pointed Bur 12S).
A pilot study investigated the precision of the software's proposed spacer thickness by aligning 5 modified Gold Standard designs of 80 μm spacer setting to their corresponding Gold Standard designs (0 μm spacer) and measuring the surface deviations. The lack of a difference in the CAD proposal produced when using normal bur settings versus EF (Extra-Fine mode) bur settings were similarly validated by aligning 5 Group 12 designs and 5 Group 12S designs to corresponding 12+EF and 12S+EF designs.
The restoration parameters are summarized in Table 1.

Secondly, 24 crowns were designed after choosing 12 and 12S bur sets respectively, resulting in two additional test groups. All other parameters were identical for the two groups. Preserving crown design, radial and occlusal spacers were set at 80 μm, minimal radial material thickness was set at 1000 μm and occlusal thickness to 1500 μm, as proposed by the software once the material selection had been made. The final designs all included all instrument parameters (consider instrument geometry, consider instrument at margin, and remove undercuts). The fitting surface of each crown had visible bur marks after selecting instrument 12 or 12S (Fig. 2).
The impact of the different burs on the internal surface of the crown proposals was quantified by aligning and measuring the surface deviation between the internal surface of the crowns from Groups 12 and 12S against the equivalent surface in the Gold Standard group. Meshlab was used to analyse the 3D data (18). Each pair of STL files was first checked for alignment errors. Any misaligned pairs were imported to WearCompare software (19) for accurate alignment with a selective surface alignment tool.
Measurements were performed using the 'Hausdorff distance' filter in Meshlab. Hausdorff distance was applied from the two test groups to the Gold Standard group. The corresponding vertices whose distance was

FIG. 2 Bur marks on the internal surface of crown design displayed by inLab SW.

smaller than 5 µm formed the outer surface of both crowns and were deleted, so that only the relevant internal surface of the design (sample mesh) was used for measurements.
The results were expressed in descriptive statistics (Fig. 3, 4, 5, Table 2) and visually displayed using color mapping (Fig. 6).
The mean of maximum, mean and standard deviation (SD) values of all compared pairs of the study groups were statistically analysed using IBM SPSS Statistics for Windows, version 26 (IBM Corp., Armonk, N.Y., USA). The difference between the two groups of data was analysed for normal distribution using Kolmogorov-Smirnov test. The difference was normally distributed and paired t-test was used to assess statistical significance ($p<0.05$). The mean values were assessed as an indication of the trueness and the SD values were discussed as an indication of precision of the designs.

RESULTS

The pilot study revealed that it was acceptable to use the 0 cement thickness crown designs (without considering bur geometry) as a proxy for the scanned preparation. The internal surface of the gold standard crown design was virtually identical to the preparation scan (mean 0.4 ± 0.08 µm). Findings also showed that the design software reliably reproduces the spacer setting, which is gradually minimised at the marginal area and has a median value of 80 ± 0 µm, as initially set. The pilot study validated that 12+EF and 12S+EF bur designs could represent 12 and 12S designs respectively.

The maximum, mean, and standard deviation (SD) distance measurements and the 95% confidence intervals (95% CI) of measurements between different crown designs (Group 12 and Group 12S) and the gold standard designs, are presented in Table 2. Box plots with median values are shown in Figures 3 and 4. The colormaps (Fig. 5) visualize the surface quality, where 200 µm has been set as the maximum value (red).
Kolmogorov-Smirnov test showed that the difference between the two groups was normally distributed, thus paired t-test was applied to each pair of measurements to assess statistical significance.
Statistical analysis showed that there was a significant difference in maximum, mean and SD measurements from the gold standard between bur set 12 and bur set 12S settings ($p<0.001$) in all cases for both incisor preparations and molar preparations.
For the incisors, Group 12S showed a higher mean maximum difference from the gold standard (531±107 µm) than group 12 (369±112 µm). For the mean distance, group 12S showed greater deviation (113±13 µm) than group 12 (88±8 µm), while the mean values for SD of group 12S (82±19 µm) were again higher than group 12 (48±14 µm) (Table 2, Fig. 3-5).
For molars, the maximum distance of group 12S had a mean value of 326.91±65.53 µm indicating a higher discrepancy compared to group 12 (245.41±49.18 µm). The mean distance of Group 12S was higher (75.45±6.67 µm) than group 12S (69.54±2.08 µm). Group 12S showed higher mean values for SD (41.91± 6.74 µm) than group 12 (31.41±3.79 µm) (Fig. 3-5, Table 2).
Example of internal fitting surface designs of group 12 is shown in Figure 6a (incisor) and 6c (molar). The

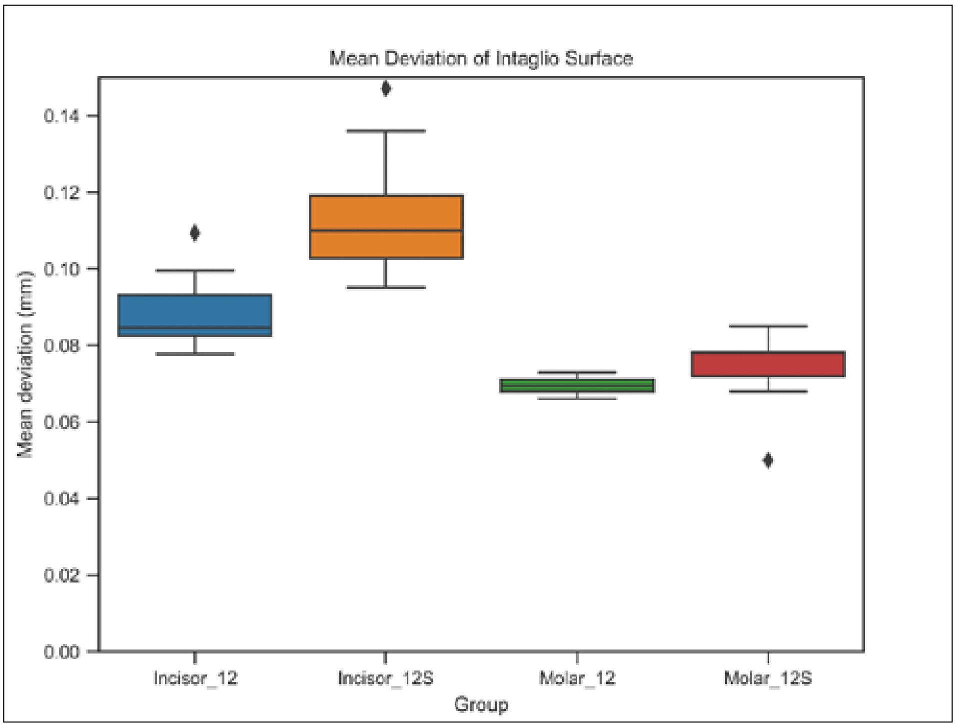

FIG. 3 Mean deviation (mm) from the molar and incisor crown designs (group 12 and group 12S) to the prepared Gold Standard group. The line indicates median value, the box upper and lower quartile, while the whiskers show overall distribution. Outliers are indicated with a diamond.

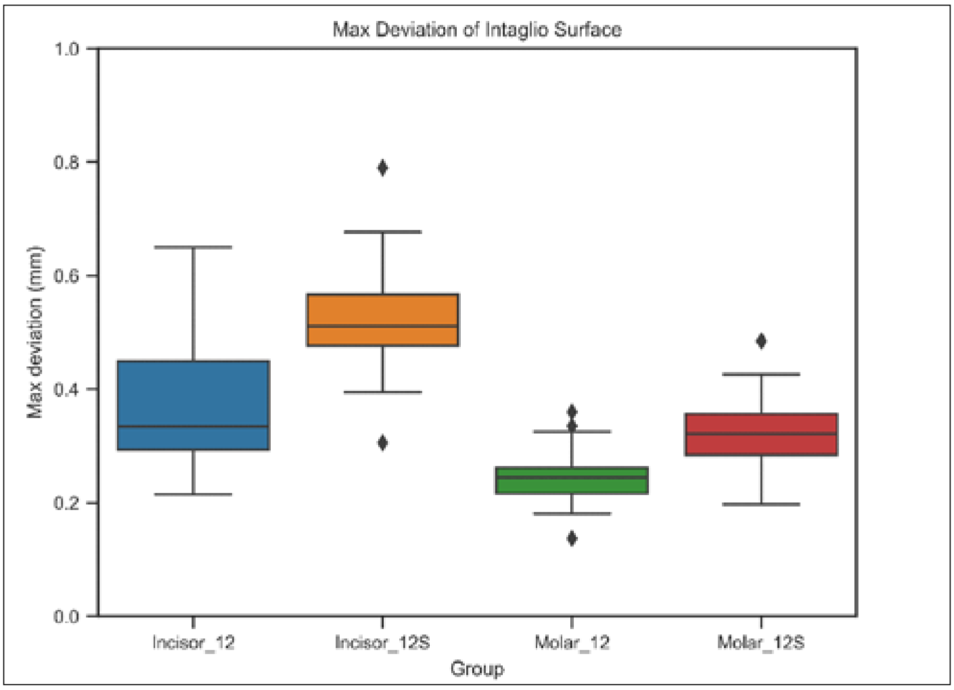

FIG. 4 Maximum deviation (mm) from the molar and incisor crown designs (group 12 and group 12S) to the prepared Gold Standard group. The line indicates median value, the box upper and lower quartile, while the whiskers show overall distribution. Outliers are indicated with a diamond.

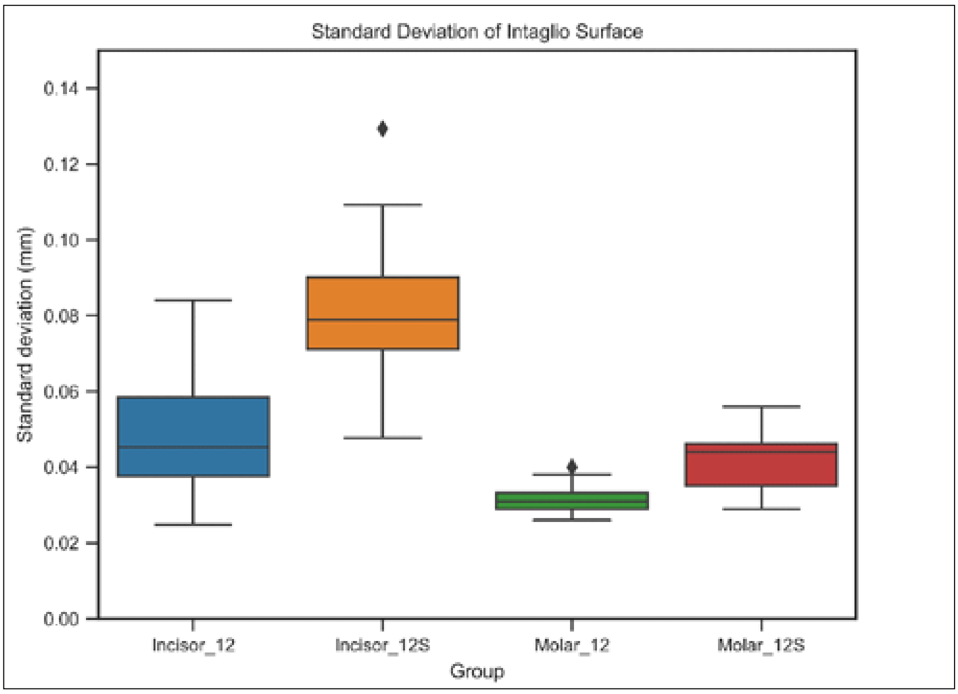

FIG. 5 Standard deviation (mm) from the molar and incisor crown designs (group 12 and group 12S) to the prepared Gold Standard group. The line indicates median value, the box upper and lower quartile, while the whiskers show overall distribution. Outliers are indicated with a diamond.

Incisors					Molars				
Group		Max	Mean	SD	Group		Max	Mean	SD
12		369±112	88±8	48±14	12		245±49	70±2	31±4
95% CI	Lower	322	84	42	95% CI	Lower	137	66	26
	Upper	416	91	54		Upper	360	73	40
12S		531±107	113±13	82±19	12S		327±66	75±7	42±7
95% CI	Lower	486	107	74	95% CI	Lower	197	50	29
	Upper	576	118	90		Upper	485	85	56

TABLE 2 Deviations of internal fit from the ideal, for incisor and molar preparations for group 12 and group 12S respectively (μm). All cases differed significantly between groups 12 and 12S ($p<0.001$ in all cases).

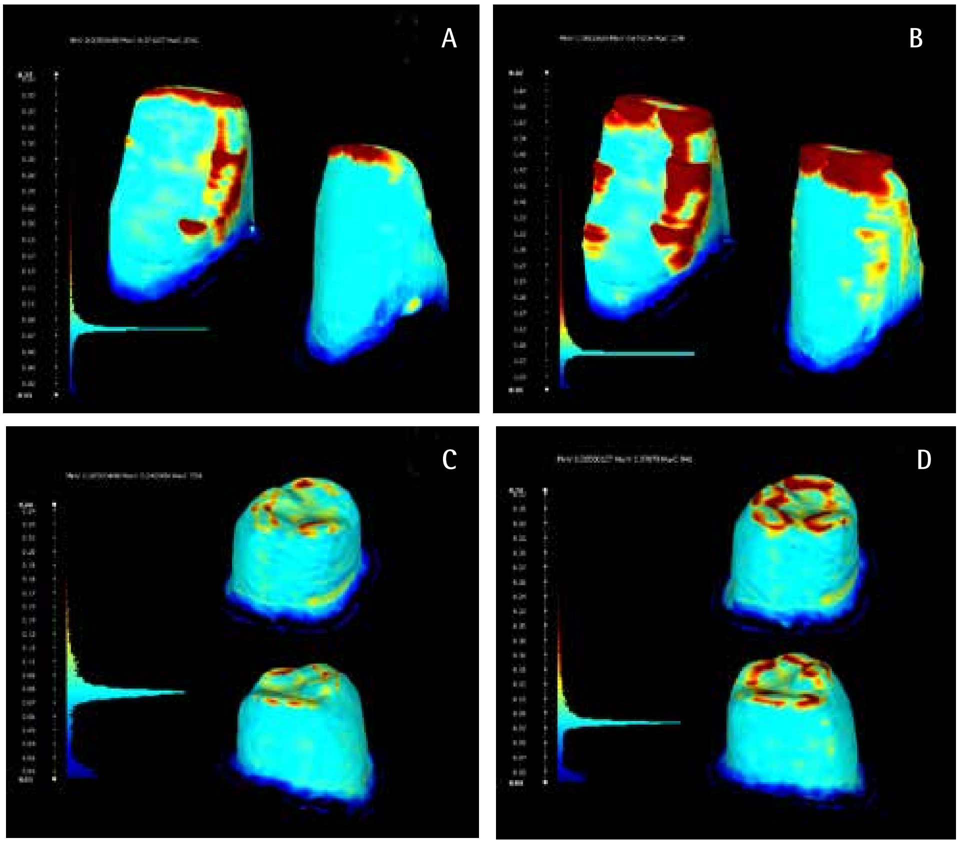

FIG. 6 Example colourmaps of measurements from the intaglio surface of the designed crowns, two viewing angles of the same design are shown.
A: from incisor (12) to gold standard cropped designs (max = 374 µm).
B: from the same incisor (12S) to gold standard cropped designs (max = 674 µm).
C: from molar (12) to gold standard cropped designs (max = 242 µm).
D: from the same molar (12S) to gold standard cropped designs (max = 370µm). 200 µm has been set as the maximum value (red), 80µm values appear cyan. The distribution of values is presented on the histogram on the left of each figure.

corresponding designs of group 12S are shown in Figure 6b and 6d respectively. Bur marks are clearly visible, the different effects between burs 12 and 12S can be seen.

DISCUSSION

The present study investigated the effect of two different bur presets (12 and 12S) for the MC XL milling machine on the quality of the proposed crown fitting surfaces (central upper incisors and lower first molars). All tested values differed significantly between the two bur set groups ($p<0.001$). The 12 bur set option performed significantly better than the 12S bur. Thus, the null hypothesis, that there was no significant difference in the surfaces designed for the two different bur sets, was rejected.
A digital method was used in this study to assess the proposed cement layer thickness of CAD/CAM crowns. 3-dimensional analyses have been proven to be accurate methods for evaluating trueness of restoration fit (15, 17, 20, 21). The present study aimed to evaluate the quality of the proposed crown fit by only exploring the single variable of the CAD software's design-suggestion for two different sets of milling burs.
Most available studies on crown fit have included milled crowns and a variety of physical internal and marginal fit assessment techniques, thus obfuscating the cause of error due to multiple variables (8, 16, 17, 20, 22). Our reported errors will underestimate the final error once physical manufacture has taken place.
Milling instrument selection may have a critical effect on the internal fit of crowns and cement thickness, making the latter non-uniform, deviating beyond 0.2 mm from the clinician's expectation in some areas. Such distribution of cement may negatively affect the crown's resistance form, which is a key factor to restoration success. Large discrepancies were located on the palatal, incisal (in anterior) and occlusal (in posterior) internal surfaces which are all load-bearing surfaces. The grooves generated by the burs reached a maximum cement space thickness of 576 µm (12S) and 416 µm (12) in the incisors, and 485 µm (12S) and 360 µm (12) in the molar crowns. These results would very likely prevent the homogeneous distribution of cement and result in pressure spots, potentially causing fractures due to poor stress distribution on the material (23).
Furthermore, by over-milling the fitting surface, the ceramic will be thinned. A carefully prepared tooth with a clearance of 1.5-2.0 mm may result in a milled crown with occlusal areas closer to 1 mm in ceramic thickness. These 'accidentally' thinner areas are likely to reside directly under the molars' cusp tips or the incisors' palatal surface, and therefore subject to the greatest functional loads, which may only serve to increase the chances of fracture or cohesive or adhesive failure. A potentially thinner ceramic material in the cusps may also decrease its resistance to dislodging forces (24).

Additional palatal and occlusal reduction (equivalent to the maximum cement thickness) is required but is not a desirable preparation strategy due to unwanted dental hard tissue destruction and additional polymerisation shrinkage that might decrease the crown adhesivity and subject failure load (25).

The findings produced by the current study were generally in accordance with the literature, with the worst fit of CAD/CAM crowns being found on occlusal areas (5,6,19). In the literature, 26 studies on CAD/CAM crowns showed mean internal fit results that varied from 51±10.8 µm to 442±22 µm (19). The current study found a statistical difference in internal fit (mean distance), between Group 12 (88±8 µm for incisors, 70±2 µm for molars) and Group 12S (113±13 µm for incisors, 75±7 µm for molars) (Fig. 5). The mean misfits that exceeded 200 µm were located on the axial walls with the highest deviation located beneath the cusp tip for molars and on the incisal edge and palatal surface for incisors. Considering that occlusal and biting forces can cause high tensile stress on occlusal and palatal surfaces of crowns, our findings can be considered to be clinically relevant.

A variety of factors can affect the decision regarding bur set selection in chairside workflow with MC XL. Apart from the 'normal/fine' and 'extra fine' options, MC XL also provides a 'fast' milling strategy, which is available for 12S, but not for 12 bur set. Thus, the need for fast one-visit treatment would impose the use of step bur 12S, at the expense of quality of fit and an increased cement layer thickness.

Anterior and posterior teeth differ in terms of shape and size. Although anterior and posterior preparation guidelines follow the same principles, anterior prepared teeth are smaller and may involve thin edges while posterior teeth have a complex anatomy. The preparation design may have an important impact on the CAD/CAM crown fit, due to milling instruments' geometry (26).

Our findings show that bur selection may significantly affect the internal surface of the designed CAD/CAM crowns. According to our findings, a 12 bur set could be a more appropriate option than 12S for the tested incisor and molar crowns as these would be less likely to suffer from 'over-milling', resulting in crowns being milled thinner than expected and involving a thicker cement layer when seating. Both incisors and molars showed the highest maximum surface deviation on the palatal, incisal and occlusal areas. The surface deviation was greater in incisors than molars. Incisors, unlike molars, had visible bur marks as steps on the palatal area (Fig. 5). These findings indicate that the clinician could benefit from being aware of the MC XL's tendency to over-mill crowns; if the findings from the present study informed clinical preparation design, the resulting crowns may improve in fit and longevity.

It is necessary to note that traditional manufacturing methods may show better internal fit of the occlusal surface of restorations than CAD/CAM fabrication, according to several studies (12, 16). It may be argued that a traditional lost-wax technique uses a well-controlled spacer and thus a pressed crown might be thicker and stronger than a CAD/CAM equivalent (27). However, other authors underline that the average quality of fit is superior for CAD/CAM systems (22).

Only crowns of upper central incisors and lower first molars were tested in the present study, therefore the results should not be immediately generalised to other types of restorations or teeth. Experiments on smaller teeth such as lateral upper or lower incisors might reveal that milling CAD/CAM crowns with burs 12 and 12S is an unacceptable option in the case of inadequate possible occlusal clearance. Other types of restorations such as inlays/onlays, veneers and implant restorations should also be investigated.

Furthemore, this study has focused on the MC XL machine and inLab design software. Considerably, more work needs to be done with a broader range of machine and software versions from different manufactures in order to assess their performance. More CAD applications and CAM burs for 4-axis or 5-axis milling machines should be examined. In addition, the experiment was limited to feldspathic ceramic parameters. This experiment was conducted *in vitro*: it did not take into consideration clinical conditions. It can be argued that *in vivo* conditions would show worse results due to scanning inaccuracies (28), while an in vitro method would examine manufacturing effects such as material importance (29) or actual bur wear (30, 31), accuracy levels (20) and calibration importance of the milling machine.

Milling the designed restorations of this study with MC XL would expose the true quality of CAD/CAM crowns *in vitro* and allow comparisons between designs and actual crowns, in order to reveal the potential level of data degradation due to CAM software and procedure inaccuracies and failures. The importance of material selection could be defined by using a variety of available CAD/CAM blocks or discs. *In vivo* investigations regarding CAD/CAM restoration internal fit and cement thickness would complete the required series of evidence in order to draw definite conclusions.

CONCLUSION

Within the limitations of this study, it can be concluded that the bur type has an impact on the internal surface of CAD/CAM crown proposals. Bur set 12 exhibited better trueness (mean) and precision (SD) values than 12S. Thus, a smaller diameter bur is more likely to correctly reproduce the crown fitting surface. The generated cement space varied within the internal surface of the crowns; the highest discrepancy was located on the occlusal surface for molars and on the incisal and palatal for incisors. These findings could help inform clinicians' expectations on the impact of milling instrument selection on internal fit and surface quality of CAD designed ceramic crowns.

Disclaimer

Both principal authors contributed equally to this work. The order of the first two author names was determined randomly.

Funding

This work was supported internally at the University of Leeds (UK).

Conflicts of Interest

The authors declare there are no conflicts of interest.

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