The marginal gaps of sequentially milled lithium disilicate crowns using two different milling units

K Tan, J Dudley*

*Adelaide Dental School, The University of Adelaide, Adelaide, SA, Australia.

ABSTRACT

Background: The purpose of this study was to compare the marginal gaps of sequentially milled lithium disilicate (LDS) crowns using two different milling units.

Methods: One lower left first molar typodont tooth prepared for an LDS crown by an undergraduate student in a simulation clinic was selected. The crown preparation was scanned by a TRIOS 3 scanner and twelve LDS crowns milled by an E4D (E4DM) and a Sirona inLab MC X5 (MCX5) milling unit using identical settings. The crowns were seated onto the original crown preparation and three vertical marginal gap measurements were taken at four locations (mid-buccal, mid-lingual, mid-mesial and mid-distal) using a stereomicroscope. The mean marginal gap (MMG) was calculated for each individual tooth surface and each crown.

Results: The MMG for the E4DM (100.40 µm) was not significantly different to the MCX5 (101.08 µm) milling unit (P = 0.8809). In both units, there was a statistically significant trend of increasing MMG with sequentially milled crowns using the same burs (E4DM P = 0.0133; MCX5 P = 0.0240).

Conclusions: The E4DM and MCX5 milling units produced LDS crowns with similar MMG's and within a clinically acceptable range but with a trend of increasing MMG when analysed sequentially. © 2022 Australian Dental Association

Keywords: Bur wear, crown, lithium disilicate, marginal gap, milling unit.

Abbreviations and acronyms: CAD = computer-aided design; CAD/CAM = computer-aided design/computer-aided manufacturing; LDS = lithium disilicate; MMG = mean marginal gap; STL = standard tessellation language.

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INTRODUCTION

The advent of computer-aided design/computer-aided manufacturing (CAD/CAM) technology in the 1980s expanded the options and materials available for constructing all-ceramic crowns. More recently, the range of milling units has grown exponentially with manufacturer claims of improved efficiency, accuracy and versatility leading to great competition in the industry. While chairside milling units are convenient, laboratory-based milling units are generally designed to handle greater production requirements. The ability to scan a crown preparation and mill a crown chairside has clear advantages including the elimination of the need for traditional impressions, reduced number of appointments and clinical time, reduced or no need for temporisation, increased patient convenience, utilisation of digital technologies and delivery of a same day crown. However, the comparison of the accuracy of the chairside technique with generally larger laboratory-based milling units has been limited.

IPS e.max CAD (Ivoclar Vivadent, Schaan, Liechtenstein) is a pre-sintered millable lithium disilicate (LDS) ceramic material first introduced in 2006. IPS e.max has excellent physical properties and a wide range of aesthetic options making it a popular choice amongst clinicians. The material is milled in a partially crystallised ‘blue state’ comprising metasilicate (Li2SiO3) crystals which are later converted to disilicate (2SiO2-Li2O) crystals during the heat crystallisation process.

Of the many factors that contribute to the clinical success of crowns, the marginal fit of the crown to the prepared tooth surface is considered the key determinant. Accurate marginal fit reduces the risk of hypersensitivity due to microleakage and reduces local plaque accumulation at the crown-tooth interface. A failure to ensure accurate marginal fit can result in the development of periodontal disease and...
potentially dental caries which might lead to pulpi-
tis.4,7 There has been a wide range of ceramic mate-
rial marginal gaps reported in the literature ranging
from 7.5 to 206.3 µm largely due to the heterogeneity
of studies.8 In particular, there have been variations in
the definition of marginal gap, different methods
employed to determine the size of the marginal gap
involving invasive and non-invasive techniques, mar-
ginal gaps measured both pre- and post-cementation,
and the use of ceramic systems that involve different
construction techniques that affect the accuracy of
fit.8 However, a widely accepted maximum clinical
marginal gaps reported in the literature ranging
from 7.5 to 206.3 µm9–11 based on the initial work
of McLean and von Fraunhofer that examined 1000
restorative gaps over a 5-year period.12

Previous studies comparing milling units from dif-
ferent manufacturing generations have shown that bur
diameter size,13,14 the milling modes used15 and the
number of milling axes14,16,17 have significant impacts
on the accuracy of fit of milled crowns. The evidence
on the accuracy of repeatedly milling crowns is lim-
ited and the effects of repetitive milling on crown sur-
face roughness have yielded no common consensus18,19 despite observation of bur degradation
over time.20,21 Studies exploring the marginal gaps of
sequentially milled crowns have been performed on
glass ceramic, zirconia and titanium prostheses
only.22,23 There are no known studies that have com-
pared the marginal gaps of sequentially milled LDS
crowns using different milling units, and specifically
comparing a chairside and laboratory milling unit.

The purpose of this study was to compare the mean
marginal gap (MMG) of sequentially milled CAD/
CAM LDS crowns using two different milling units. The null hypotheses were:
(1) There was no difference in the overall MMG of LDS
crowns constructed using the two milling units.
(2) There was no difference in the individual location
MMG of LDS crowns constructed when analysed
by separate milling unit and by comparison
between the milling units.
(3) There was no difference in the MMG of sequentially
constructed LDS crowns for each milling unit.

MATERIALS AND METHODS

Ethics approval was not required by the relevant
human research ethics committee.

Crown designs

In a previous study,24 24 Columbia typodont model
(Columbia Dentoform, Long Island City, NY, USA)
lower left first molars were prepared for full-coverage
LDS (IPS e.max, Ivoclar Vivadent) crowns by fourth
year undergraduate students in a simulation clinic. In

Marginal gap measurement

Each LDS crown was seated onto the original crown
preparation with firm digital pressure and secured
with a removable adhesive in a polyvinylsiloxane base
(Fig. 1 and 1b) with four indicators to standardise the
measurement locations (mid-buccal, mid-distal, mid-
lingual and mid-lingual). The visco-elastic removable
adhesive adapted over the contours of the crown and
tooth and permitted temporary fixation of the crown
to the crown preparation without damaging the sam-
ple. The custom-made polyvinylsiloxane base allowed
the tooth to lie flat in a standardised position. The
seated crowns were positioned perpendicular to the
stereomicroscope (Nikon SMZ25, Nikon Instruments,
Melville, NY, USA). An extended depth of focus tool
was used to account for variations in the z-plane
caused by horizontal discrepancy and allowed mea-
surement of the true vertical marginal discrepancy. A 2.0× objective lens at a fixed magnification range
A DS-Ri1 CCD camera (Nikon Instruments) mounted on the microscope transmitted live images to the Nikon NIS-Elements AR-Duo control software (Nikon Instruments) to measure the vertical distance between the external surface of the crown margin and the preparation finish line (Fig. 2). Three measurements were taken at each of the four sites for each crown resulting in 12 measurements per tooth and 144 measurements per milling unit (Fig. 3). All measurements were taken by the same operator.

### Statistical analysis

All measurements for all tooth surfaces were averaged to calculate an overall MMG for the E4DM and MCX5 units. The MMG for each crown was calculated by averaging all measurements for all individual locations. For each milling unit, the MMG for each location (mid-buccal, mid-distal, mid-lingual, mid-mesial) was calculated by averaging all measurements for the individual location. A linear mixed-effects model was used for regression modelling and an F-test for comparison of the variances. A Jonckheere-Terpstra test was used to analyse the trend of MMG’s over time (SAS 9.4, SAS Institute, Cary, NC, USA). The level of statistical significance was set at $P = 0.05$. The threshold for being considered clinically acceptable was set at 120 \( \mu \text{m} \).^{12}

### Bur wear

The burs from each milling unit were viewed under a scanning electron microscope (Fei ESEM Quanta 450, FELMI-ZFE, Graz, Austria) at 500 x magnification and imaged using microscope control software (xT, FEI, Hillsboro, OR, USA) before milling commenced, at a mid-milling sequence point and when the bur was indicated for replacement. Bur surface topography was captured using secondary electron imaging and surface composition was captured using backscatter imaging.$^{26}$

There was no established and standardised method available to quantitatively measure the wear and diamond particle loss so this was limited to observation.

### RESULTS

#### Overall MMG

The MMG for the E4DM (100.40 ± 11.69 \( \mu \text{m} \)) was not significantly different to the E4DM (101.08 ± 11.25 \( \mu \text{m} \)) unit ($P = 0.8809$). A comparison of the standard deviation between the two scanners revealed no significant difference in variability ($F = 1.03, P = 0.9183$).

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**Fig. 1** (a) Lithium disilicate crown seated onto its corresponding original crown preparation secured in a polyvinylsiloxane base. (b) Scanned crown preparation.
Within the E4DM and MCX5 groups, the linear mixed-effects model revealed a significant difference in MMG between locations ($P < 0.0001$). In both the E4DM and MCX5 groups, the mid-mesial margin recorded the largest MMG and was above the clinically accepted threshold of 120 µm (Figs 4 and 5), whereas the mid-lingual margin recorded the lowest MMG.

In comparing the two milling units, the MMG of the mid-buccal and mid-distal surfaces were the two surfaces that showed a statistically significant difference from each other ($P < 0.001$).

**MMG with sequentially milled crowns**

The Jonckheere-Terpstra Test revealed a significant trend of increasing MMG with sequentially milled crowns using the same burs in the E4DM ($P = 0.0133$) and MCX5 ($P = 0.0240$) groups (Figs 6 and 7). Following the replacement of the burs, the MMG reduced to a lower value that approximated that of the initial crowns milled in the sequence. The MMG for each of the 24 crowns constructed was below the clinically accepted threshold except for MC11 which was the final crown milled before the MCX5 burs required changing.

**Bur wear with sequentially milled crowns**

The images of bur wear with sequential milling are presented in Fig. 8. The blunting of the burs was evidenced by loss of the nickel matrix holding the diamond particles as well as loss of diamond particles. The main E4DM bur displayed a more noticeable...
pull-out of diamond grit particles at the bur tip while the MCX5 bur predominantly displayed abrasive loss of the nickel matrix holding the diamond particles.

DISCUSSION

This study found no difference in the overall MMG of LDS crowns constructed using the two milling units, therefore the first null hypothesis was accepted. There was a significant difference in the individual location MMG of LDS crowns constructed by both milling units when analysed separately and also when the individual locations for the milling units were compared, and there was a significant difference in the MMG of sequentially milled LDS crowns using the same burs for each milling unit, therefore the second and third null hypotheses were rejected.

Variability of MMG

There was great variation between the smallest and largest MMG within each milling unit. The crown preparation was recruited from a series of preparations completed by undergraduate students and contained common pitfalls such as uneven preparation finish lines and overtapering. Interproximal margins are a challenging area to prepare in inexperienced hands and the mesial margin was conceivably the more challenging. Previous analyses of the crown preparations in this study series revealed that preparations were prone to uneven or jagged finish lines in the mesial and distal regions. It was foreseeable that students had difficulty viewing and accessing the mesial margin as typically indirect vision was required. The accurate scanning of sub-optimally refined margins could have resulted in reduced accuracy of fit which aligns with previous reasoning that preparation errors rather than milling had a significant effect on marginal gap. Additionally, poor surface finish of the preparation might cause premature binding and prevent complete seating of the crown on the tooth, resulting in an artificially enlarged marginal gap.

Individual location MMG

The E4DM and MCX5 groups displayed significantly different individual location MMG’s for both mid-buccal and mid-distal surfaces (Figs 4 and 5). This is proposed to be attributable to STL file conversion

![MMG for E4DM by individual location](image)

Fig. 4 MMG for E4DM by individual location.
and/or data interpretation differences between the older E4DM unit and the newer MCX5 unit. However, it does not explain the similar mid-lingual and mid-mesial margins which were the most accurate and least accurate, respectively, in both groups. It is possible that both milling units were less discerning for the mid-lingual margin as there is a limit to the additional accuracy possible as the marginal gap more closely approaches the ideal value of 0 μm. A larger sample size and greater number of measurements per crown would assist in corroborating this finding.

Fig. 5 MMG for MCX5 by individual location.

Fig. 6 MMG of E4DM with sequentially milled crowns using the same burs.
Increasing MMG with sequentially milled crowns

The trend of increasing MMG with sequentially milled crowns using the same burs was observed in both milling groups and might be attributable to diamond bur wear leading to poorer cutting efficacy. Changes to the working end surface of a diamond bur such as wearing down and loss of diamond particles, loss of matrix and the introduction of defects into the diamond particle microstructure affect the accuracy of the milling process by diminishing cutting efficacy which might in turn negatively impact the marginal fit. A decrease in cutting ability might lead to increased friction and stress on the ceramic block which might translate to defects and microfractures on the ceramic leading to larger marginal gaps. It has been reported that increased use of the diamond bur resulted in greater gap readings on the intaglio of milled ceramic crowns suggesting that loss of abrasive particles resulting in bur wear might be linked with a poorer crown to tooth adaptation.

Variability in bur wear rates between milling units

The MCX5 constructed 11 LDS crowns before the unit requested a change of the main milling bur, whereas the E4DM requested a bur change after nine crowns (Figs 6 and 7). Both milling units produced LDS crowns with an overall MMG within a clinically acceptable range with the exception of MCX5 crown MC11 which was the last crown constructed before the mill requested a bur change. While the E4DM used a single dedicated 1.1 mm rounded tip bur for milling the internal surface, the MCX5 used four burs of diameters of 2.2, 1.4, 1.2 and 0.6 mm interchangeably to progressively mill the intaglio and external crown surfaces. There was a more even distribution of bur wear and loss of diamond particles across the four burs, as observed in the scanning electron microscope images. The greater number of burs used and differential rate of bur wear explains the MCX5 unit milling a larger number of crowns before the burs required changing in comparison to the E4DM unit. The recognition and measurement of bur wear are challenging and relies either on the unit to detect bur wear or on applying a limit to the number of crowns milled with a bur set before replacement.

Differences in milling units

The E4DM was released to the marketplace approximately 10 years ago and is a 3-axis chairside mill whereas the MCX5 unit is a more recent 5-axis commercial mill. While there have been great advances in milling technology and efficiency, the results of the current study suggest the two milling units had no significant influence on the marginal gap of LDS crowns. Instead, the proposed technological advances might have had a greater impact on milling efficiency, ease of operator use and advertising potential.

Limitations

The crown preparation selected for this study was performed by one of a group of undergraduate students on a manikin in a simulation clinic environment which allowed reproduction of some but not all clinical factors. On one hand, the crown preparation was not an ideal or benchtop preparation and on the other hand, it did not include potentially confounding factors such as blood, saliva, access and patient compliance that are typically present in vivo. The crown preparation was limited to a lower left molar and it is acknowledged...
typodont teeth have different to natural tooth structure in surface hardness. Student crown preparations are prone to overtapering which might make the crown more susceptible to ‘rocking’ on the preparation giving rise to artificially enlarged and diminished marginal gaps on one side and its contralateral side. An ideal preparation by an experienced operator might yield different research outcomes.
The marginal gap involves three dimensions and this study acknowledges the external vertical marginal gap was measured at selected locations and extrapolated to represent the overall crown marginal gap. Three-dimensional measurement methods such as microcomputed tomography would enhance the accuracy and reliability and facilitate further investigation of the effect of bur wear on crown fit by assessing both the internal fit and horizontal discrepancy. It would be ideal to obtain measurements at a large number of different locations using a large sample size. In the current study, the measurement protocol was standardised across all samples and performed by a single trained researcher. Future research might investigate a wider array of milling units and ceramic materials and develop a quantitative measurement of bur wear to examine its effect on the quality of the milled crown.

Within the limitations of this in vitro study, the E4DM and MCX5 milling units produced LDS crowns with similar overall MMG’s and within a clinically acceptable range. There was a statistically significant difference in the individual location MMG of LDS crowns constructed by both milling units when analysed separately and also when the individual locations for the milling units were compared. For both milling units, there was a statistically significant trend of increasing MMG with sequentially milled crowns using the same burs.

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DISCLOSURE STATEMENT
There is no conflict of interest to declare.

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ETHICS
The study was performed at The University of Adelaide and ethics approval was not required by The University of Adelaide Human Research Ethics Committee.

REFERENCES
1. Blatz MB, Conejo J. The current state of chairside digital dentistry and materials. Dent Clin North Am 2019;63:175–197.
2. Willard A, Gabriel Chu TM. The science and application of IPS e.max dental ceramic. Kaohsiung J Med Sci 2018;34:238–242.
3. Zarone F, Di Mauro MI, Ausiello P, Ruggiero G, Sorrentino R. Current status on lithium disilicate and zirconia: a narrative review. BMC Oral Health 2019;19:134.
4. Contrepois M, Soenen A, Bartala M, Laviole O. Marginal adaptation of ceramic crowns: a systematic review. J Prosthodont 2013;110:447–454.
5. Alqahtani F. Marginal fit of all-ceramic crowns fabricated using two extraoral CAD/CAM systems in comparison with the conventional technique. Clin Cosmet Investig Dent 2017;9:13–18.
6. Souza RO, Özcan M, Pavanelli CA, et al. Marginal and internal discrepancies related to margin design of ceramic crowns fabricated by a CAD/CAM system. J Prosthodont 2012;21:94–100.
7. Al-Haideri H, Ibraheem A. Evaluation of the marginal and internal fitness of monolithic CAD/CAM zirconia crowns using two software design and different open system milling machines. Indian J Forensic Med Toxicol 2019;13:224.
8. Nawalleh NA, Mack F, Evans J, Mackay J, Hatamleh MM. Accuracy and reliability of methods to measure marginal adaptation of crowns and FDPs: a literature review. J Prosthodont 2013;22:419–428.
9. Holmes JR, Bayne SC, Holland GA, Sulik WD. Considerations in measurement of marginal fit. J Prosthet Dent 1989;62:405–408.
10. Boitelle P, Mawussi B, Tapie L, Fromentin O. A systematic review of CAD/CAM fit restoration evaluations. J Oral Rehabil 2014;41:853–874.
11. Renne W, Wolf R, Kessler R, McPherson K, Meninato AS. Evaluation of the marginal fit of CAD/CAM crowns fabricated using two different chairside CAD/CAM systems on preparations of varying quality. J Esthet Restor Dent 2015;27:194–202.
12. McLean JW, von Fraunhofer JA. The estimation of cement film thickness by an in vivo technique. Br Dent J 1971;131:107–111.
13. Neves FD, Prado CJ, Prudente MS, et al. Micro-computed tomography evaluation of marginal fit of lithium disilicate crowns fabricated by using chairside CAD/CAM systems or the heat-pressing technique. J Prosthet Dent 2014;112:1134–1140.
14. Bosch G, Ender A, Mehl A. A 3-dimensional accuracy analysis of chairside CAD/CAM milling processes. J Prosthodont 2014;112:1425–1431.
15. Sadid-Zadeh R, Katsavochristou A, Squires T, Simon M. Accuracy of marginal fit and axial wall contour for lithium disilicate crowns fabricated using three digital workflows. J Prosthodont 2020;123:121–127.
16. Hamza TA, Ezzat HA, El-Hossary MMK, El Megid Katamish HA, Shokry TE, Rosenstiel SF. Accuracy of ceramic restorations made with two CAD/CAM systems. J Prosthodont 2013;109:83–87.
17. Beuer F, Schweiger J, Edelhoff D. Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. Br Dent J 2008;204:505–511.
18. Madruga CFL, Bueno MG, Dal Piva AMO, et al. Sequential usage of diamond bur for CAD/CAM milling; effect on the roughness, topography and fatigue strength of lithium disilicate glass ceramic. J Mech Behav Biomed Mater 2019;91:326–334.
19. Yara A, Ogura H, Shinya A, et al. Durability of diamond burs for the fabrication of ceramic crowns using dental CAD/CAM. Dent Mater J 2005;24:134–139.
20. Roperto RC, Lopes FC, Porto TS, et al. CAD/CAM diamond tool wear. Quintessence Int 2018;49:781–786.
21. Lebon N, Tapie L, Vennat E, Mawussi B. Influence of CAD/CAM tool and material on tool wear and roughness of dental prostheses after milling. J Prosthet Dent 2015;114:236–247.

22. Al Hamad KQ, Al-Rashdan RB, Al-Rashdan BA, Baba NZ. Effect of milling protocols on trueness and precision of ceramic crowns. J Prosthodont 2021;30:171–176.

23. Song DB, Han MS, Kim SC, Ahn J, Im YW, Lee HH. Influence of sequential CAD/CAM milling on the fitting accuracy of titanium three-unit fixed dental prostheses. Materials (Basel) 2021;14:1401.

24. Tran J, Dudley J, Richards L. All-ceramic crown preparations: an alternative technique. Aust Dent J 2017;62:65–70.

25. Kwong B, Dudley J. A comparison of the marginal gaps of lithium disilicate crowns fabricated by two different intraoral scanners. Aust Dent J 2020;65:150–157.

26. Saghiri MA, Asgar K, Lotfi M, et al. Back-scattered and secondary electron images of scanning electron microscopy in dentistry: a new method for surface analysis. Acta Odontol Scand 2012;70:603–609.

27. Zhang Y, Dudley J. The influence of different cement spaces on the marginal gap of CAD/CAM all-ceramic crowns. Aust Dent J 2019;64:167–174.

28. Batson ER, Cooper LF, Duqum I, Mendonça G. Clinical outcomes of three different crown systems with CAD/CAM technology. J Prosthet Dent 2014;112:770–777.

29. Yin L, Song X, Song Y, Huang T, Li J. An overview of in vitro abrasive finishing & CAD/CAM of bio-ceramics in restorative dentistry. Int J Mach Tools Manuf 2006;46:1013–1026.

30. Tomita S, Shin-Ya A, Gomi H, et al. Machining accuracy of CAD/CAM ceramic crowns fabricated with repeated machining using the same diamond bur. Dent Mater J 2005;24:123–133.

31. Keeling A, Wu J, Ferrari M. Confounding factors affecting the marginal quality of an intra-oral scan. J Dent 2017;39:33–40.

32. Vaz CB, Margarida I, Carracho PCL, Fausto J. Marginal fit of zirconia copings fabricated after conventional impression making and digital scanning: an in vitro study. J Prosthet Dent 2020;124:223.e1–223.e6.

33. Al Hamad KQ, Al Quran FA, Aljalam SA, Baba NZ. Comparison of the accuracy of fit of metal, zirconia, and lithium disilicate crowns made from different manufacturing techniques. J Prosthodont 2019;28:497–503.

34. Dudley J. The use of artificial teeth for post-core techniques in a pre-clinical fixed prosthodontics undergraduate teaching program: an evaluation of student experience. J Int Oral Health 2021;13:144–150.

35. Kim JH, Jeong JH, Lee JH, Cho HW. Fit of lithium disilicate crowns fabricated from conventional and digital impressions assessed with micro-CT. J Prosthet Dent 2016;116:551–557.

36. Piras FF, Ferruzzi F, Ferrairo BM, Ramalho IS, Bonfante EA, Rubo JH. Analysis of correlation between optical and microtomography measurements of cementation space in CAD-CAM ceramic crowns. J Prosthet Dent 2020;124:87.e1–87.e6.

*Address for correspondence:
Associate Professor James Dudley
Adelaide Dental School
10 Floor, Adelaide Health and Medical Sciences Building
The University of Adelaide
North Terrace, Adelaide 5005
Australia
Email: james.dudley@adelaide.edu.au