©Operative Dentistry, 2020, **45-2,** 143-150

Volumetric Cuspal Deflection of Premolars Restored With Different Paste-like Bulk-fill Resin Composites Evaluated by Microcomputed Tomography

G Demirel • IH Baltacioglu • ME Kolsuz • M Ocak • B Bilecenoglu • K Orhan

Clinical Relevance

The use of paste-like bulk-fill composites for class II MOD cavities reduces cuspal deflection compared to the paste-like conventional resin composite.

SUMMARY

Objectives: The aim of this study was to measure the volumetric cuspal deflection of premolars restored with different paste-like bulk-fill resin composites using microcomputed tomography (micro-CT).

Methods and Materials: A total of 35 freshly extracted human maxillary second premolars were selected for this study. Standardized large MOD cavities were prepared in each premolar with a bucco-lingual width of 4 mm and a cavity depth of 4 mm measured from the palatal cusp tip. After cavity preparation, all samples were scanned immediately using a micro-CT system. After the initial micro-CT scanning, restorative procedures were performed. Four groups received different paste-like bulk-fill composites—Beautifil-Bulk Restorative (BBR), Admira Fusion x-tra (AFX), x-tra fill, and Sonic Fill—and the control group received a conventional universal composite and Clearfil Majesty Esthetic (CME). Immediately after the restorative procedure, each

Gülbike Demirel, PhD, DDS, Department of Restorative Dentistry, School of Dentistry, Ankara University, Ankara, Turkey

Ismail Hakki Baltacioglu, PhD, DDS, Department of Restorative Dentistry, School of Dentistry, Ankara University, Ankara, Turkey

Mehmet Eray Kolsuz, PhD, DDS, Department of Dentomaxillofacial Radiology, School of Dentistry, Ankara University, Ankara, Turkey

Mert Ocak, PhD, lecturer, Vocational School of Health, Ankara University, Ankara, Turkey

Burak Bilecenoğlu, DDS, PhD, associate professor, Department of Anatomy, School of Dentistry, Ankara, Turkey

*Kaan Orhan, PhD, professor, Department of Dentomaxillofacial Radiology, School of Dentistry, Ankara University, Ankara, Turkey. OMFS IMPATH Research Group, Department of Imaging & Pathology, Faculty of Medicine, University of Leuven Oral & Maxillofacial Surgery, University Hospitals Leuven, Leuven, Belgium

*Corresponding author: University Hospitals Leuven, Kapucijnenvoer 7 blok a Leuven 3000, Belgium; e-mail: kaan.orhan@uzleuven.be

DOI: http://doi.org/10.2341/19-019-L

tooth was scanned by micro-CT in the same manner as the initial scanning. The buccal and palatal regions of each restoration were evaluated separately in terms of cuspal deflection. One-way analysis of variance was used to compare the effect of the composite resin, and multiple comparisons were performed by the Tukey test with a level of significance of $\alpha = 0.05$.

Results and Discussion: Multiple comparisons showed that teeth restored with the conventional paste-like composite and CME (control) had significantly different cuspal deflection from those filled with paste-like bulk-fill composites ($p<0.05$). Among the bulk-fill composites, a significant difference was observed between BBR and AFX ($p<0.05$).

Conclusions: Paste-like bulk-fill resin composites had significantly lower cuspal deflection than the conventional paste-like resin composite tested.

INTRODUCTION

Bulk-fill resin composites have gained popularity among clinicians for posterior restorations due to improvements of materials and enhanced curing,[1] which controls the effect of curing stresses.[2,3] Although the conventional 2-mm incremental layering procedure is needed for conventional composites, advanced bulk-fill composites can be cured as a single bulk layer with a thickness of 4 to 6 mm.[4] According to their viscosity, these materials can be classified into "flowable/base" or "paste-like/full-body" types. Due to their low amount of filler, flowable bulk-fill composites have less wear resistance; therefore, completing the top layer with a composite, which has a high amount of filler, is necessary.[5,6] The paste-like bulk-fill materials contain higher amounts of filler. These composites are particularly viscous, sculptable, and highly wear resistant, and capping of the top layer is not necessary.[6]

Bulk-fill composites also contain monomers, similar to conventional composites. During the polymerization reaction, the monomers approach each other,[7] resulting in a volumetric shrinkage of composite material.[8] Shrinkage can create stress in the composite structure, and the dental tissue can also cause marginal gaps, microleakage, and cuspal deflection.[9,10] Cuspal deflection may lead over time to microcrack propagation, enamel cracks, crazing, reduction in fracture resistance of the restored tooth, postoperative sensitivity, pulpal problems, and, in extreme cases, cusp fracture.[11,12]

In the literature, several techniques have been reported to calculate cuspal deflection in wide class II cavities with composite restorations, and values of up to 50 μm of mean cusp deformation have been reported.[13-17] These studies used microscopy, strain gauges, flexible ribbons, linear variable differential transformers, and trans-tooth illumination techniques. With these methodologies, cuspal deflection can be measured in one dimension, giving a linear result. Two- and three-dimensional (2D and 3D) microcomputed tomography (micro-CT) allows evaluation of the restorative material itself and adaptation to the dental structures with high spatial resolution.[18] This technique has proved its adequacy to evaluate the polymerization contraction vectors,[19] and it can represent both the pattern and the volume of polymerization shrinkage[20] and calculate the shrinkage volume of the resin composites.[18,21] Although a few studies have examined cuspal deflection using micro-CT, no previous study has analyzed the 3D volumetric cuspal deflection of premolars restored with different paste-like bulk-fill composites using micro-CT.

The aim of this study was to measure the volumetric cuspal deflection of premolars restored with different paste-like bulk-fill resin composites using micro-CT. The null hypothesis was that paste-like bulk-fill resin composites would not generate different amounts of cuspal deflection from conventional resin composites.

METHODS AND MATERIALS

Tooth Selection and Cavity Preparation

A total of 35 freshly extracted human maxillary second premolars that were free from caries, hypoplastic defects, or cracks were selected for this study. The maximum buccal-palatal width (BPW) and the maximum mesio-distal width (MDW) of each premolar were measured prior to any work using a digital caliper (Mitutoyo, Kawasaki, Japan) with a tolerance of 10 μm, and the teeth were distributed into five groups (n=7) such that the variance of the mean BPW and MDW between groups was less than 5%. Teeth were embedded in a cube-shaped plastic mold 2 cm in diameter using chemically cured acrylic resin, and the mold extended 2 mm cervical to the cemento-enamel junction to simulate the position of the tooth in the alveolar bone and to prevent reinforcement of the crown by the base. Four spheres were placed around

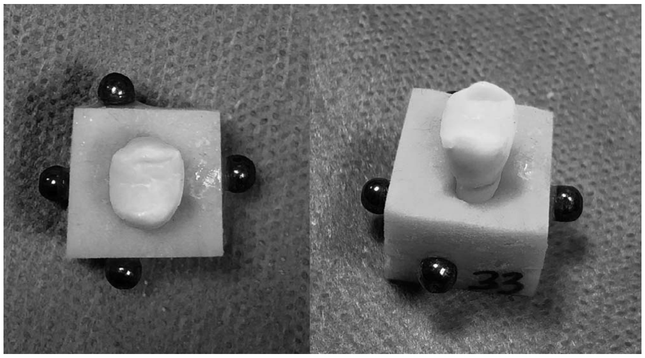

Figure 1. *Sample with spheres placed around the acrylic base.*

the acrylic base, which functioned as stable reference areas, as shown in Figure 1.

Standardized large MOD cavities were prepared in each premolar with a bucco-lingual width of 4 mm and a cavity depth of 4 mm measured from the palatal cusp tip. The dimensions of each cavity preparation were verified using a digital caliper. The cavities were prepared without proximal boxes to minimize the preparation variation.[22] The buccal and lingual walls of each cavity were prepared parallel to each other.[22,23] Cavosurface margins were prepared without beveling. Cavities were prepared with a straight diamond bur with a rounded end (#881H-012, Hager & Meisinger GmbH, Neuss, Germany) using a high-speed hand piece with copious air-water spray. The bur was changed after each cavity preparation. Teeth with pulp exposure were excluded from the study.

Initial Micro-CT Scanning

All samples were scanned immediately after cavity preparation using a micro-CT system (Bruker Skyscan 1275, Kontich, Belgium). The teeth were positioned with the buccal surface facing the X-ray tube to ensure standardization. The scanning conditions were as follows: 100 kVp, 120 mA, 0.5-mm Al/Cu filter, 9.1-μm pixel size, and rotation at 0.1 steps. Flat field calibration was carried out prior to each scan; moreover, the manufacturer's protocol was followed to minimize ring artifacts. Each specimen was rotated 360° during the five-minute integration time. The mean time of scanning was approximately 70 minutes. The beam hardening correction and other parameters, including optimal contrast, were set according to the manufacturer's instructions.

Restorative Procedures

After the initial micro-CT scanning, to eliminate the dehydration caused by the dry environment of the scanning device, the samples were rehydrated for 30 minutes in distilled water, as in the study by Shirani and others,[24] and then restorative procedures were performed. Four groups received different paste-like bulk-fill composites—Beautifil-Bulk Restorative (BBR), Admira Fusion x-tra (AFX), x-tra fill (XTF), and Sonic Fill (SF)—and the control group received a conventional universal composite and Clearfil Majesty Esthetic (CME) (Table 1).

Metal matrix bands (Adapt SuperCap Matrix no 2182, Kerr-Hawe, Bioggio, Switzerland) were seated for each group. The enamel was etched for 15 seconds with 35% orthophosphoric acid (K-ETCHANT Syringe, Kuraray Noritake Dental Inc, Okayama, Japan), rinsed for 10 seconds, and then dried with cotton pellets, leaving the surface moist, according to the manufacturer's directions. This procedure was followed by the application of universal adhesive (Single Bond Universal, 3M ESPE, St Paul, MN, USA) to the entire cavity with a rubbing action for 20 seconds. The excess solvent was evaporated with a gentle air spray for five seconds. The bonding agent was cured for 10 seconds with an LED curing light (Elipar DeepCure-S LED Curing Light, 3M ESPE). The output power was periodically monitored with the radiometer of the curing unit to ensure an intensity of at least 1000 mW/cm^2. The four bulk-fill composites were applied to the prepared cavities in single-bulk increments, while the conventional composite was applied in three horizontal increments. Each layer was cured according to the manufacturers' instructions (Table 1).

Cuspal Deflection Analysis by Micro-CT

Immediately after the restorative procedure, each tooth was scanned by micro-CT in the same manner as the initial scanning. NRecon software (ver. 1.7.4.2, SkyScan, Brüker, Kontich, Belgium) and CTAn (ver. 1.18.4.0, SkyScan, Brüker) were used for imaging and measurement of the samples. For reconstruction, the algorithm by Feldkamp and others[25] was used to achieve axial, 2D slices. For the reconstruction parameters, ring artifact correction and smoothing were fixed at zero, and the beam artifact correction was fixed at 50%. Cross images were then reconstructed from the whole volume using micro-CT. The reconstructed images were superimposed using DataViewer software (ver. 1.5.6.2, SkyScan, Brüker). Reference points that were distant from the area affected by shrinkage were selected to align the different images of the prepared restored teeth. The spherical balls that were attached before scanning were used for this

Table 1: *Materials Used in the Study (Information as Disclosed by the Manufacturers)*

Material	Shade	Lot Number	Matrix Composition	Filler % by Weight	Polymerization Shrinkage by Volume (%)	Recommended Thickness	Recommended Curing Time and Light Intensity for Each Layer	Number of Layer of Samples	Manufacturer
Beautifil-Bulk Restorative (BBR)	Universal	071406	Bis-GMA, UDMA, Bis-MPEPP, TEGDMA, S-PRG filler based on fluoroboroaluminosilicate glass, polymerization initiator, pigments, others	87	1.7	4 mm	10 s 1000 mW/cm^2	1 (4 mm)	Shofu (Kyoto, Japan)
Admira Fusion x-tra (AFX)	Universal	1813298	Organically modified silicic acid, silicon dioxide nanofillers (20–50 nm), silicon oxide–based hybrid fillers (1 μm)	84	1.25	4 mm	20 s $\geq$1000 mW/cm^2 $\times$ 3	1 (4 mm)	VOCO GmbH (Cuxhaven, Germany)
x-tra fill (XTF)	Universal	1749292	Inorganic filler in a methacrylate matrix (bis-GMA, UDMA, TEG-DMA)	86	1.7	4 mm	10 s $\geq$800 mW/cm^2	1 (4 mm)	VOCO
Sonic Fill (SF)	A2	1012336	Bis-GMA, TEGDMA, EBPDMA, UDMA, SiO_2, glass, oxide	83.5	1.6	4 mm	10 s 1000 mW/cm^2	1 (4 mm)	Kerr Corp. (Orange, CA, USA)
Clearfil Majesty Esthetic (CME)	A2	4H0173	Bis-GMA, hydrophobic aromatic dimethacrylate, hydrophobic aliphatic methacrylate, silanated barium glass filler, prepolymerized organic filler, dl-camphorquinone, initiators, accelerators, pigments, others	78	1.9	1.5 mm	20 s $>$300 mW/cm^2	3 (1.5 mm + 1.5 mm + 1 mm)	Kuraray (Okayama, Japan)

Abbreviations: Bis-GMA, bisphenol A glycidyl methacrylate; UDMA, urethane dimethacrylate; Bis-MPEPP, 2,2-bis[(4-methacryloxy polyethoxy)phenyl]propane; TEGDMA, triethylene glycol dimethacrylate; S-PRG, surface reaction–type prereleased glass ionomer; EBPDMA, ethoxylated bisphenol A dimethacrylate.

purpose. The prepared tooth image (reference) and the restored tooth image (target) were superimposed, and the difference in volume was determined by image subtraction. The resulting image represented the volume of the cuspal deflection caused by the polymerization shrinkage of the resin composite restoration (Figures 2 and 3).

CTAn software was used for visualization and calculation of this subtracted image. A region of interest (ROI) was drawn to include the entire specimen within the sample using CTAn software, and all specifications of the program were used to analyze the microarchitecture of each sample. Once the appropriate ROI (in volume) was selected, "binary images" were obtained, and an appropriate grayscale threshold was selected to distinguish the enamel, dentin, and composite fillings. A thresholding (binarization) process was used, which entailed processing the range of gray levels to obtain a superimposed image of only black/white pixels. Despeckling was also performed to remove white speckles in the 2D image that were less than 10 voxels. The buccal and palatal regions of each restoration were evaluated separately in terms of cuspal deflection. The total cuspal deflection volume values are expressed in mm^3.

Statistical Analysis

The volume of cuspal deflection after restoration was analyzed using the Shapiro-Wilk test for normality and equality of variances (the Levene test), followed by a parametric statistical test. One-way analysis of variance (ANOVA) was used to compare the effect of the composite resin, and multiple comparisons were performed using the Tukey test. All tests used a significance level of $\alpha = 0.05$, and all analyses were conducted with the statistical program GraphPad Prism (ver. 6.0).

RESULTS

The cuspal deflection values for the tested composites are shown in Table 2. One-way ANOVA showed that the resin composite type had a significant effect on cuspal deflection ($p<0.0001$).

Multiple comparisons (Table 2) showed that teeth restored with the conventional paste-like composite and CME (control) had significantly different cuspal

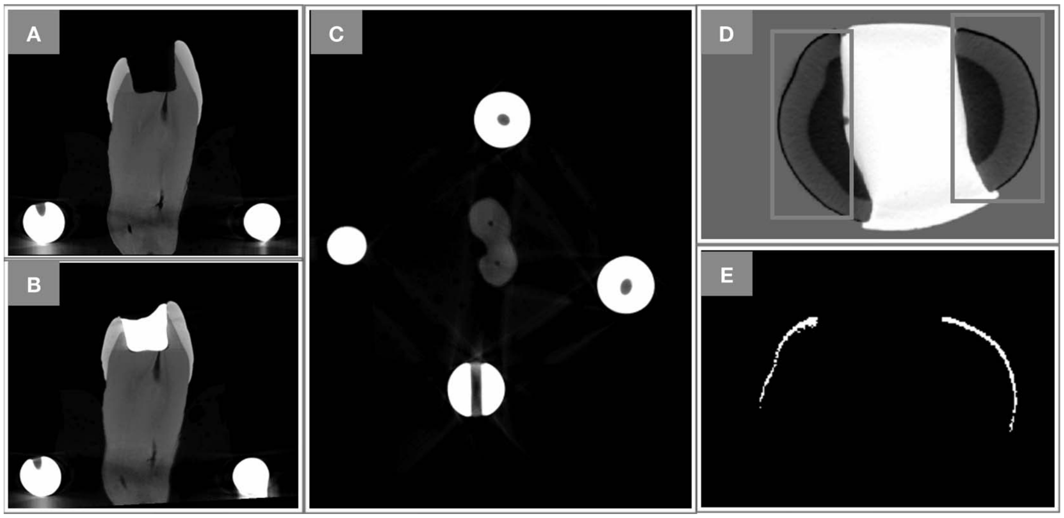

Figure 2. *Measurement of the cuspal deflection using micro-CT. (A): Sagittal section of a prepared tooth. (B): Sagittal section of a tooth immediately after restoration. (C): Overlapping of the prepared and restored tooth using spheres. (D): Rectangular regions of interest of the difference image. (E): Binarization of the difference between the prepared and restored tooth (white area).*

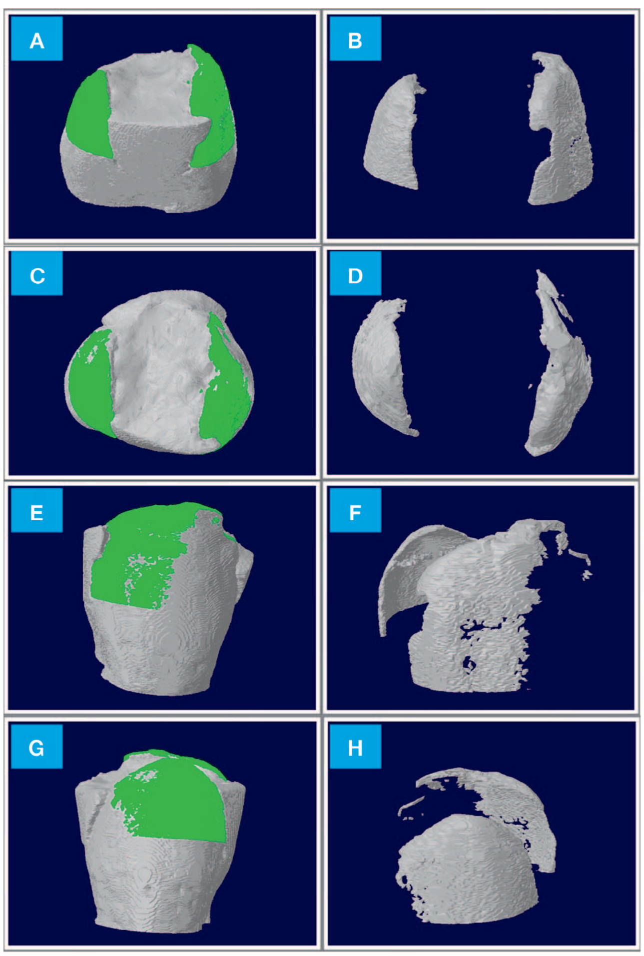

Figure 3. *Representative images of the volume of cuspal deflection. Deflected cusp regions in proximal (A, B), occlusal (C, D), buccal (E, F), and palatinal (G, H) views.*

deflection than those filled with paste-like bulk-fill composites ($p<0.05$). Among bulk-fill composites, a significant difference was observed between BBR and AFX ($p<0.05$).

DISCUSSION

This study investigated the effect of four types of paste-like bulk-fill composites on the volumetric cuspal deflection of maxillary premolar teeth compared to a conventional paste-like composite. Due to polymerization shrinkage, all tested composite groups showed an inward deflection of the cusps, which is consistent with the results of other studies.[14,23,26-30] All paste-like bulk-fill resin composites showed less volumetric cuspal deflection than the conventional paste-like composite group. Thus, the null hypothesis was rejected.

The amount of cuspal deflection is directly related to the amount of tooth structure loss.[31] Therefore, in the present study, large MOD cavity preparations were performed on maxillary premolar teeth to weaken tooth structure and promote cuspal deflection. The dimensional differences of the premolar teeth used in the study were set to a maximum of 5% for standardization and to enable comparison with other cuspal deflection studies.[28]

Although inexpensive and simple methods are available to measure cuspal deflection, these methods measure only linear values between two points on the tooth structure.[31] However, micro-CT is useful to evaluate the volumetric differences.[29] Micro-CT enables the visualization of effects across

Table 2: *Means and Standard Deviations of Cuspal Deflection of Tested Groups*

Resin Composite Type	Total Cusp Deflection (mean – mm^3)	Standard Deviation	Difference $p < 0.05$*
Beautifil-Bulk Restorative (BBR)	−5.658	0.0699	B
Admira Fusion x-tra (AFX)	−5.066	0.2471	C
x-tra fill (XTF)	−5.258	0.2235	BC
Sonic Fill (SF)	−5.339	0.2561	BC
Clearfil Majesty Esthetic (CME) (**Control**)	−7.235	0.5223	A

** No significant difference between groups shown with the same letter.*

the entire end and can analyze the boundary conditions of the exact tooth cavity.[31] In addition, Oliveira and others[29] showed a strong correlation between cuspal deflection values measured using the micro-CT method and those measured using the strain gauge method. Therefore, cuspal deflection was measured by micro-CT in this study.

The difference between the cuspal deflection values of the bulk-fill composites and the conventional composite in the present study could be due to two factors or a combination thereof. One factor was the chemical composition of the different composites, and the other was the incremental (three layers and three sessions of light curing) restorative procedure of the conventional composite. The results of this study are consistent with those of other studies comparing paste-like bulk-fill composites and conventional paste-like composites.[23,29,32] In contrast, a study by Tsujimoto and others[30] reported that paste-like bulk-fill resin composites showed cuspal deflection similar to conventional resin composites. That study used aluminum blocks instead of extracted teeth and investigated the simulated cuspal deflection of paste-like bulk-fill and conventional resin composites with a micrometer and a confocal laser-scanning microscope. The discrepancy between our study and their results might be due to the difference in the methodology or the difference in the type of composite that was compared. Another study investigated the cuspal deflection of premolars restored with three paste-like bulk-fill composite resins and one low-shrinkage silorane-based restorative material.[14] The researchers reported that silorane-based composites caused less cuspal deflection than paste-like bulk-fill composites. Since cuspal deflection is directly caused by polymerization shrinkage, that study clearly demonstrates that the limited shrinkage behavior of the silorane-based composite caused less cusp movement than methacrylate-based composites.

Another finding of the current study was that BBR showed higher volumetric cuspal deflection than AFX among the bulk-fill composites. This difference might be related to the different chemical compositions of these resins. AFX is an Ormocer-based composite, while BBR contains many different monomers. These composites also contain different types and amounts of fillers.

Although composites are termed bulk fills, these commercially available composites differ in their chemical composition. To provide a 4-mm polymerization depth, every manufacturer organizes its composite structure with different types and quantities of monomers; different types, amounts, shapes, and sizes of fillers; and different photoinitiators,[5,6] and these components differ in each composite. These varied structures also require different amounts of curing light energy for adequate polymerization.[33] Because many variables exist, it is difficult to compare these composites with each other, which limits the studies that can be performed.

This study has some limitations. The major limitation involved the insertion technique and total polymerization energy. Conventional paste-like composite cannot be used for 4-mm bulk polymerization and was applied by an incremental technique. The polymerization time varied for composite groups according to the manufacturer's instructions. Therefore, the total energy applied to the composite groups also varied. Instead of applying equal energy to all composites, each composite was cured according to the manufacturer's specified curing time and energy instructions to simulate clinical conditions. These conditions might have affected the results. The second limitation was that composite resins absorb water in the oral environment, which causes hygroscopic expansion and can neutralize the negative effects of polymerization shrinkage and relieve cuspal deflection.[29,34] Since the early effects of the resin materials were examined, no hygroscopic expansion occurred this study. The third limitation of the study was the cavity type and dimensions. Currently, the use of adhesive restorations results in smaller cavity preparations. Large MOD cavities are usually observed in the replacement of amalgam fillings or teeth undergoing endodontic treatment due to excess caries. Therefore, the type of cavity used in this study is not a common cavity preparation, but to better observe the shrinkage properties of the materials, these large cavities with weak and stretchable walls were used in the study, similar to previous studies.[27,28] The fourth limitation of this study was the microcrack evaluation. Although enamel fractures are one of the most important results of polymerization shrinkage, their detection methods include subjective observations, such as transillumination.

Many studies have examined the cuspal deflection of bulk-fill composites *in vitro*. *In vitro* studies provide information about the general characteristics of the materials, but their interpretations of the intraoral environment are based on speculation. Studies are needed that evaluate cuspal deflection with an intraoral scanner or similar devices in an intraoral environment and that examine the early and long-term effects by evaluating both patient complaints and restoration status using intraoral evaluation criteria.

CONCLUSIONS

Within the limitations of this study, it can be concluded that paste-like bulk-fill resin composites resulted in significantly less cuspal deflection than the conventional paste-like resin composite tested. Among the bulk-fill resin composites, BBR produced greater volumetric cuspal deflection than AFX.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the Ankara University Faculty of Dentistry Ethics Committee. The approval code for this study is 2019/01 No:01/05.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 7 March 2019)

REFERENCES

1. Leprince JG, Palin WM, Hadis MA, Devaux J, & Leloup G (2013) Progress in dimethacrylate-based dental composite technology and curing efficiency *Dental Materials* **29(2)** 139-156. 10.1016/j.dental.2012.11.005

2. Algamaiah H, Sampaio CS, Rigo LC, Janal MN, Giannini M, Bonfante EA, Coelho PG, Reis AF, & Hirata R (2016) Microcomputed tomography evaluation of volumetric shrinkage of bulk-fill composites in class II cavities *Journal of Esthetic and Restorative Dentistry*. 10.1111/jerd.12275

3. El-Damanhoury H & Platt J (2014) Polymerization shrinkage stress kinetics and related properties of bulk-fill resin composites *Operative Dentistry* **39(4)** 374-382. 10.2341/13-017-l

4. Furness A, Tadros MY, Looney SW, & Rueggeberg FA (2014) Effect of bulk/incremental fill on internal gap formation of bulk-fill composites *Journal of Dentistry* **42(4)** 439-449. http://dx.doi.org/10.1016/j.jdent.2014.01.005

5. Chesterman J, Jowett A, Gallacher A, & Nixon P (2017) Bulk-fill resin-based composite restorative materials: A review *British Dental Journal* **222(5)** 337-344 10.1038/sj.bdj.2017.214.

6. Van Ende A, De Munck J, Lise DP, & Van Meerbeek B (2017) Bulk-fill composites: A review of the current literature *Journal of Adhesive Dentistry* **19(2)** 95-109. 10.3290/j.jad.a38141

7. Tsujimoto A, Barkmeier WW, Takamizawa T, Latta MA, & Miyazaki M (2016) Mechanical properties, volumetric shrinkage and depth of cure of short fiber-reinforced resin composite *Dental Materials Journal* **35(3)** 418-424. 10.4012/dmj.2015-280

8. Kaisarly D & Gezawi ME (2016) Polymerization shrinkage assessment of dental resin composites: A literature review *Odontology* **104(3)** 257-270. 10.1007/s10266-016-0264-3

9. Baltacioglu IH, Kamburoglu K, Irmak O, Geneci F, Ocak M, Uzuner MB, & Celik HH (2017) Marginal integrity of self-adhering flowable composites used as liner under class II restorations: a comparative in vitro micro-CT study *Journal of Adhesion Science and Technology* **31(24)** 2719-2729. 10.1080/01694243.2017.1317472

10. Karaman E & Ozgunaltay G (2013) Cuspal deflection in premolar teeth restored using current composite resins with and without resin-modified glass ionomer liner *Operative Dentistry* **38(3)** 282-289. 10.2341/11-400-l

11. Mantri SP & Mantri SS (2013) Management of shrinkage stresses in direct restorative light-cured composites: A review *Journal of Esthetic and Restorative Dentistry* **25(5)** 305-313. 10.1111/jerd.12047

12. Lee MR, Cho BH, Son HH, Um CM, & Lee IB (2007) Influence of cavity dimension and restoration methods on the cusp deflection of premolars in composite restoration *Dental Materials* **23(3)** 288-295. 10.1016/j.dental.2006.01.025

13. Alomari QD, Reinhardt JW, & Boyer DB (2001) Effect of liners on cusp deflection and gap formation in composite restorations *Operative Dentistry* **26(4)** 406-411.

14. Behery H, El-Mowafy O, El-Badrawy W, Saleh B, & Nabih S (2016) Cuspal deflection of premolars restored with bulk-fill composite resins *Journal of Esthetic and Restorative Dentistry* **28(2)** 122-130. 10.1111/jerd.12188

15. Campodonico CE, Tantbirojn D, Olin PS, & Versluis A (2011) Cuspal deflection and depth of cure in resin-based composite restorations filled by using bulk, incremental and transtooth-illumination techniques *Journal of the American Dental Association* **142(10)** 1176-1182. https://doi.org/10.14219/jada.archive.2011.0087

16. McCullock AJ & Smith BG (1986) In vitro studies of cuspal movement produced by adhesive restorative materials *British Dental Journal* **161(11)** 405-409.

17. Meredith N & Setchell DJ (1997) In vitro measurement of cuspal strain and displacement in composite restored teeth *Journal of Dentistry* **25(3-4)** 331-337.

18. Hirata R, Clozza E, Giannini M, Farrokhmanesh E, Janal M, Tovar N, Bonfante EA, & Coelho PG (2015) Shrinkage assessment of low shrinkage composites using micro-computed tomography *Journal of Biomedical Materials Research Part B: Applied Biomaterials* **103(4)** 798-806. 10.1002/jbm.b.33258

19. Chiang YC, Rosch P, Dabanoglu A, Lin CP, Hickel R, & Kunzelmann KH (2010) Polymerization composite shrinkage evaluation with 3D deformation analysis from microCT images *Dental Materials* **26(3)** 223-231. 10.1016/j.dental.2009.09.013

20. Sampaio CS, Chiu KJ, Farrokhmanesh E, Janal M, Puppin-Rontani RM, Giannini M, Bonfante EA, Coelho PG, & Hirata R (2017) Microcomputed tomography evaluation of polymerization shrinkage of class I flowable resin composite restorations *Operative Dentistry* **42(1)** e16-e23. 10.2341/15-296-l

21. Algamaiah H, Sampaio CS, Rigo LC, Janal MN, Giannini M, Bonfante EA, Coelho PG, Reis AF, & Hirata R (2017) Microcomputed tomography evaluation of volumetric shrinkage of bulk-fill composites in class II cavities *Journal of Esthetic and Restorative Dentistry* **29(2)** 118-127. 10.1111/jerd.12275

22. Jafarpour S, El-Badrawy W, Jazi HS, & McComb D (2012) Effect of composite insertion technique on cuspal deflection using an in vitro simulation model *Operative Dentistry* **37(3)** 299-305. 10.2341/11-086-l

23. Elsharkasi MM, Platt JA, Cook NB, Yassen GH, & Matis BA (2018) Cuspal deflection in premolar teeth restored with bulk-fill resin-based composite materials *Operative Dentistry* **43(1)** e1-e9. 10.2341/16-072-l

24. Shirani F, Malekipour MR, Sakhaei Manesh V, & Aghaei F (2012) Hydration and dehydration periods of crown fragments prior to reattachment *Operative Dentistry* **37(5)** 501-508. 10.2341/10-130-l

25. Feldkamp LA, Goldstein SA, Parfitt AM, Jesion G, & Kleerekoper M (1989) The direct examination of three-dimensional bone architecture in vitro by computed tomography *Journal of Bone and Mineral Research* **4(1)** 3-11. 10.1002/jbmr.5650040103

26. Francis AV, Braxton AD, Ahmad W, Tantbirojn D, Simon JF, & Versluis A (2015) Cuspal flexure and extent of cure of a bulk-fill flowable base composite *Operative Dentistry* **40(5)** 515-523. 10.2341/14-235-l

27. McHugh LEJ, Politi I, Al-Fodeh RS, & Fleming GJP (2017) Implications of resin-based composite (RBC) restoration on cuspal deflection and microleakage score in molar teeth: Placement protocol and restorative material *Dental Materials* **33(9)** e329-e335. 10.1016/j.dental.2017.06.001

28. Moorthy A, Hogg CH, Dowling AH, Grufferty BF, Benetti AR, & Fleming GJ (2012) Cuspal deflection and micro-leakage in premolar teeth restored with bulk-fill flowable resin-based composite base materials *Journal of Dentistry* **40(6)** 500-505. 10.1016/j.jdent.2012.02.015

29. Oliveira LRS, Braga SSL, Bicalho AA, Ribeiro MTH, Price RB, & Soares CJ (2018) Molar cusp deformation evaluated by micro-CT and enamel crack formation to compare incremental and bulk-filling techniques *Journal of Dentistry* **74** 71-78. 10.1016/j.jdent.2018.04.015

30. Tsujimoto A, Nagura Y, Barkmeier WW, Watanabe H, Johnson WW, Takamizawa T, Latta MA, & Miyazaki M (2018) Simulated cuspal deflection and flexural properties of high viscosity bulk-fill and conventional resin composites *Journal of the Mechanical Behavior of Biomedical Materials* **87** 111-118. https://doi.org/10.1016/j.jmbbm.2018.07.013

31. Gonzalez Lopez S, Sanz Chinesta MV, Ceballos Garcia L, de Haro Gasquet F, & Gonzalez Rodriguez MP (2006) Influence of cavity type and size of composite restorations on cuspal flexure *Medicina Oral, Patología Oral y Cirugía Bucal* **11(6)** e536-e540.

32. Politi I, McHugh LEJ, Al-Fodeh RS, & Fleming GJP (2018) Modification of the restoration protocol for resin-based composite (RBC) restoratives (conventional and bulk fill) on cuspal movement and microleakage score in molar teeth *Dental Materials* **34(9)** 1271-1277. 10.1016/j.dental.2018.05.010

33. Zorzin J, Maier E, Harre S, Fey T, Belli R, Lohbauer U, Petschelt A, & Taschner M (2015) Bulk-fill resin composites: Polymerization properties and extended light curing *Dental Materials* **31(3)** 293-301. https://doi.org/10.1016/j.dental.2014.12.010

34. Meriwether LA, Blen BJ, Benson JH, Hatch RH, Tantbirojn D, & Versluis A (2013) Shrinkage stress compensation in composite-restored teeth: Relaxation or hygroscopic expansion? *Dental Materials* **29(5)** 573-579. https://doi.org/10.1016/j.dental.2013.03.006