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The cuspal deflection caused by dental composite polymerization shrinkage analyzed by digital holography

Ispitivanje uticaja polimerizacione kontrakcije dentalnog kompozita na deformaciju kvržica zuba digitalnom holografijom

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Abstract

Background/Aim. Polymerization shrinkage of filling materials is one of the main disadvantages of adhesive restorative dentistry. The objective of the study was to measure tooth cusps deflection caused by polymerization shrinkage of a resin-based dental material (RDM) in real-time using digital holographic interferometry (DHI) in two groups of cavities restored with and without an additional wall. Simultaneously, internal tooth mechanical behavior was monitored. **Methods.** Standardized three class I cavities were prepared on third molar teeth. The teeth were cut in two halves in the longitudinal plane, obtaining six samples for the study (now with class II cavities), divided into two groups (group G1 – with the additional wall, group G2 – without it), and mounted in aluminum blocks. The cavities were filled with the RDM, cured with a light emitting diode (LED) for 40 sec from the occlusal direction, and monitored during the curing and post-curing period using DHI. Data were analyzed using the Student's *t*-test for independent samples and the Anderson-Darling test, with an alpha level of 0.05. **Results.** At the end of the examined period, the samples from the group G1 showed significantly increased tooth cusps deflection [t (10) = 4.7; *p* = 0.001] compared to samples from the group G2. **Conclusion.** Within the limitations of this study, it was concluded that the presence of the additional wall simulating a dental matrix band had a significant influence on the increase and prolonged deflection of tooth cusps during the examined RDM polymerization shrinkage.

Key words:
composite resins; interferometry; polymerization; tooth.

Apstrakt

Uvod/Cilj. Polimerizaciona kontrakcija dentalnog materijala za ispunu je jedan od glavnih problema u restorativnoj stomatologiji. Cilj rada bio je da se detektuje naprezanje kvržica zuba izazvano polimerizacionom kontrakcijom dentalnog materijala na bazi smole (DMS) u realnom vremenu, primenom digitalne holografske interferometrije (DHI) u dve grupe kaviteta restauriranih sa i bez dodatnog zida. Uporedo je praćeno mehaničko ponašanje zubnog tkiva. **Metode.** Na humanim trećim molarima pripremljena su tri standardizovana kaviteta klase I. Zubi su presečeni na dve polovine u uzdužnoj ravni. Dobijeno je šest uzoraka (sada sa kavitetima klase II) podeljenih u dve grupe (grupa G1 – sa dodatnim zidom, grupa G2 – bez njega) i fiksiranih u aluminijumske kalupe. Kaviteti su potom ispunjeni DMS, osvetljeni tokom 40 s svetlosno-emitujućom diodom (*light emitting diode* – LED) iz okluzalne projekcije i ispitivani tokom i nakon perioda osvetljavanja primenom DHI. Podaci su analizirani Studentovim *t*-testom za nezavisne uzorke i Anderson-Darlingovim testom, sa nivoom značajnosti alfa od 0,05. **Rezultati.** Na kraju ispitivanog perioda, uzorci iz grupe G1 pokazali su značajno veću deformaciju kvržica zuba [t (10) = 4,7; *p* = 0,001], u poređenju sa uzorcima iz grupe G2. **Zaključak.** U okviru ograničenja ove studije, zaključeno je da je prisustvo dodatnog zida, simulirajući dentalnu matricu, značajno uticalo na povećano i produženo naprezanje kvržica zuba prilikom polimerizacione kontrakcije ispitivanog DMS.

Ključne reči:
smole, kompozitne; interferometrija; polimerizacija; zub.

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Introduction

Despite the continuous improvements in the field of resin-based dental materials (RDM), polymerization shrinkage of filling materials is one of the main disadvantages that remains of interest in adhesive restorative dentistry. During material setting, polymerization shrinkage stress (PSS) is generated at the tooth-restoration interface, which is considered responsible for several negative clinical effects that may arise, including debonding, leakage, postoperative sensitivity, secondary caries, cusps deflection, and crack formation in enamel/dentin [1, 2]. Regarded as a physical process, PSS depends on several factors such as volume/weight percentages of the resin matrix, filler formulation, restorative procedure, and cavity configuration (C-factor) [3]. Hence, PSS is a highly non-uniform and multifactorial phenomenon that cannot be measured directly [4–6]. Consequently, experimental tests need to be carried out to investigate the constraints imposed on the bonded restorations [7–10] and to estimate interface problems in adhesive reconstructions caused by PSS [10, 11]. On the other hand, direct monitoring of secondary phenomena, such as tooth cusps deflection, can provide indirect vision into PSS development [12–16].

Digital holographic interferometry (DHI) is a laser optic technique suitable for non-destructive and contactless measurements of submicron changes in highly asymmetrical objects with micrometer precision [16, 17]. The efficiency of classical holographic interferometry in the field of dental biomechanics was previously studied [18, 19], while DHI is a relatively new testing method. Due to the digital nature of the method (digital camera, computer software), enabling fast and simple recording and reconstruction of holographically generated interference images, DHI has become a valuable tool in different fields of science and technology [20].

The bulk of the mineralized tooth tissue is composed of dentin which supports the overlying hard and brittle enamel in the part of the tooth crown [21]. These two specific calcified tissues are joined by the dentin-enamel junction (DEJ), described as a natural multilevel interface that plays a vital role in the accommodation of stress [21–23]. Considering the anisotropic histological structure of enamel and dentin, it is of utmost importance for the clinical practice to appreciate the impact of PSS on each of the surrounding hard tooth tissues.

On the other hand, it was previously identified that confinement imposed on the RDM by bonding to tooth cavity walls affects the level of PSS [8, 9]. This specific relationship, described through the concept of the C-factor and defined as the ratio of bonded to unbonded (free) surfaces of the restoration [24], still contributes to layering restorative procedures [25, 26] or bulk filling techniques [27]. Meanwhile, during proximal tooth cavity reconstruction, the creation of the missing tooth part is built by using a metal band (matrix band) to perform a proper tooth crown reconstruction. Therefore, the impact of this additional constraint on the RDM, caused by the matrix band, was examined in this study.

The objective of this study was to measure tooth cusps deflection during the RDM polymerization shrinkage, in real-time using DHI, in two groups of cavities restored with and without an additional wall. Simultaneously, internal tooth mechanical behavior throughout the curing and post-curing period of the RDM was monitored. Following the aforementioned aim, the hypothesis that there is no significant difference in tooth cusps deflection at the end of the examined period between the two groups was presumed.

Methods

Ten third molar teeth extracted for pericoronitis, periodontal disease, or orthodontic reasons were collected before the beginning of the experiment at the Department of Oral Surgery, Dentistry Clinic of Vojvodina, Novi Sad, Serbia. The teeth were cleaned of residual periodontal ligament and debris and stored in distilled water (23 ± 1˚C). All clinical procedures were performed under the ethical guidelines of the Ethics Committee of the Faculty of Medicine, University Novi Sad (No 01-39/32/1, from April 15, 2021). Due to numerous anatomical variances of third molar teeth, all gathered teeth were measured following the previously defined criteria by Politi et al. [28] – a maximum buccal-palatal width (BPW) of 10.25–10.75 mm, and the presence of four cusps (two buccal and two palatal). As a result, three third molar teeth were included in the study.

Sample preparation

Class I cavities were prepared on the three selected teeth using a high-speed handpiece (300,000 rpm) with water spray and a round diamond bur for cavity preparation with perpendicular walls to the pulp floor and rounded internal line angles. In the interest of better control of the biological variability of human teeth, cavity preparation was performed following relative rather than absolute measures as follows: the width was two-thirds of the BPW, the occlusal isthmus was prepared to half of the BPW, the mesial-distal extension was performed towards the end of the central groove preserving marginal ridge integrity, and the axial depth was set at 2 mm (measured from the end of the central groove). In that manner, the integrity of the tooth cusps and marginal ridges was preserved, avoiding potential inconsistency in tooth tissue mechanical behavior during PSS.

To estimate the mechanical behavior of internal tooth tissue, teeth were cut in half to expose dentin, enamel, and DEJ since DHI can only visualize surface changes of non-transparent objects for the wavelength of the selected light source [16]. Samples were cut longitudinally (vestibule-oral direction) in two halves according to the study of Xia et al.[16] resulting in six samples for the analysis with two tooth cusps each (buccal and palatal), permitting the internal tooth mechanical behavior evaluation. In the next step, the samples were mounted in aluminum blocks using dental gypsum (Marmorock 20; Dr. Böhme & Schöps™ GmbH, EN 26873/ ISO 6873, type IV) to the level of the enamel-cement junction, ensuring the visibility of the tooth crown and appropriate mechanical stability necessary for the experiment. Before applying the resin bonding adhesive system (Single bond universal adhesive® – 3M™ Deutschland GmbH, LOT No.

663414), the cavities were cleansed under copious water irrigation and etched with phosphoric acid (Gel etchant 37.5% phosphoric acid, Kerr Italia™ s.r.l, LOT No. 3596305) using the total-etch technique (30 sec enamel, 15 sec dentin) and then water-rinsed once again. The bonding system was then applied following the manufacturer's instructions and cured for 10 sec with a LED light source (SmartLite IQ2® LED curing light, Dentsply®, Model No. 200, Serial No. B21581, 500 mW/cm^2).

Two groups of three samples each were formed so that one-half of every tooth was included in the first group (G1) and the second group (G2), respectively. On the G1 group samples, a piece of a thin microscopic cover glass was added along the proximal side of the cavity during tooth fixation, simulating a matrix band (normally used in clinical practice to restore class II cavities) and maintaining the visibility of internal tooth tissues, while the samples in the G2 group were mounted without it serving as a negative control. The prepared cavities were restored by the bulk filling technique, using a single increment of material per cavity.

Resin-based dental material

For the RDM, a nano-filler resin composite was used (Filtek Ultimate Universal Restorative®), A2 body shade, 3M ESPE ™ USA, lot No. N867954, matrix: bisphenol-A-diglycidyl ether dimethacrylate (bis-GMA), urethane dimethacrylate (UDMA), triethylene glycol dimethacrylate (TEGDMA), bisphenol-A-polyethylene glycol diether dimethacrylate (bis-EMA), polyethylene glycol dimethacrylate (PEGDMA). The filler consisted of non-agglomerated/non-aggregated 20 nm silica filler, non-agglomerated/non-aggregated 4–11 nm zirconia filler, and aggregated zirconia/silica cluster filler (average cluster particle size 0.6–10 μm). Filler loading was 78.5% by weight and 63.3% by volume.

Finally, samples were fixed in the DHI setup. After fixation, the polymerization process was activated with the LED light source, applied from the occlusal direction at a distance of 1mm from the sample surface, and using a continuous curing mode of 40 sec. The study included the examination of the curing and post-curing period lasting a total of 320 sec (~ 5 min).

Experimental setup

The tooth cusps deflection was directly monitored in real-time using a custom-made DHI setup with a single laser beam expanded by a diverging lens and a spherical mirror (Figure 1). In that manner, observation and laser light illumination of the sample from both sides (front and rear) was enabled, while the region of interest was the cut side of the sample, providing a vision of the internal tooth tissues (Figures 2a–3b). By generating all the necessary beams from the same input beam, excellent mechanical stability of the setup required for the holographic experiment was obtained [17]. In this experiment, a diode-pumped solid-state, frequency-doubled Nd: Vanadate (Nd: YVO_4) laser was used that provided single-frequency green output (Coherent® Verdi V5, 532 nm wavelength, 5 W maximum power). The power output of 500 mW was enough for this experiment, while the linewidth of the laser was less than 5 MHz, guaran-

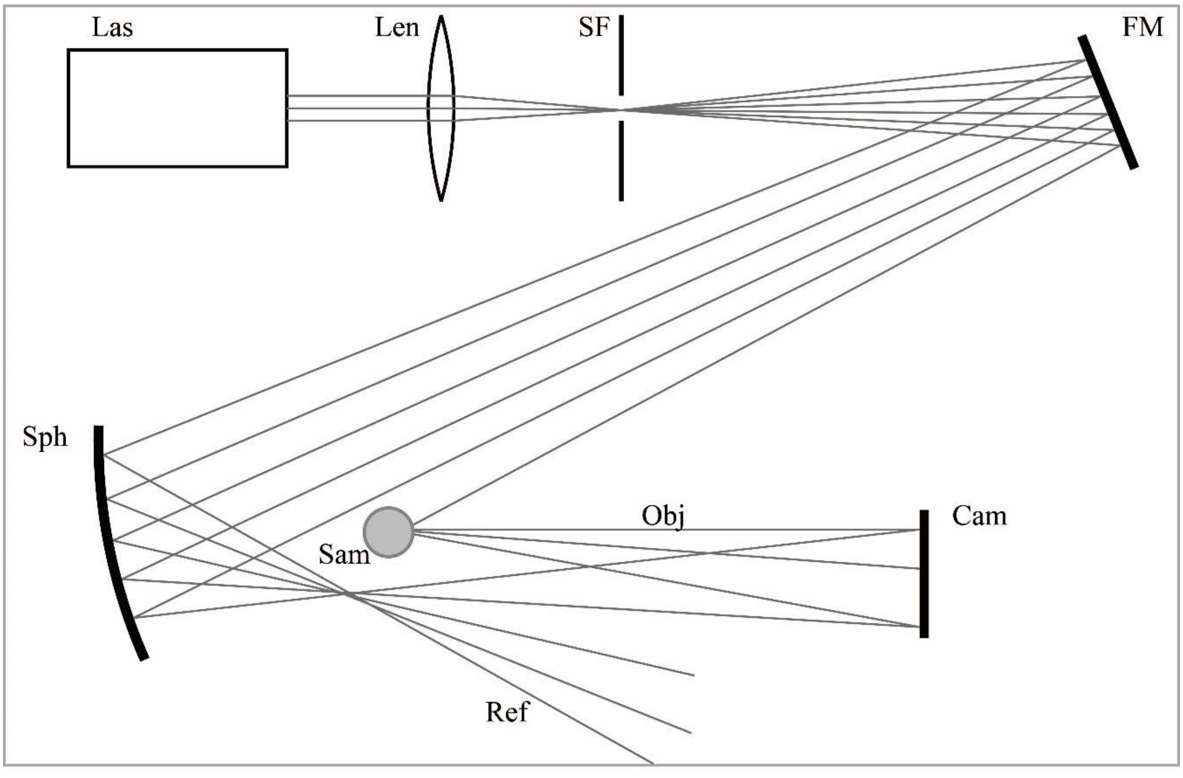

Fig. 1 – Custom made digital holographic interferometry (DHI) setup.
Las – laser; Len – lens; SF – spatial filter; FM – flat mirror; Sph – spherical mirror; Sam – sample; Ref – reference beam; Obj – object beam; Cam – camera.

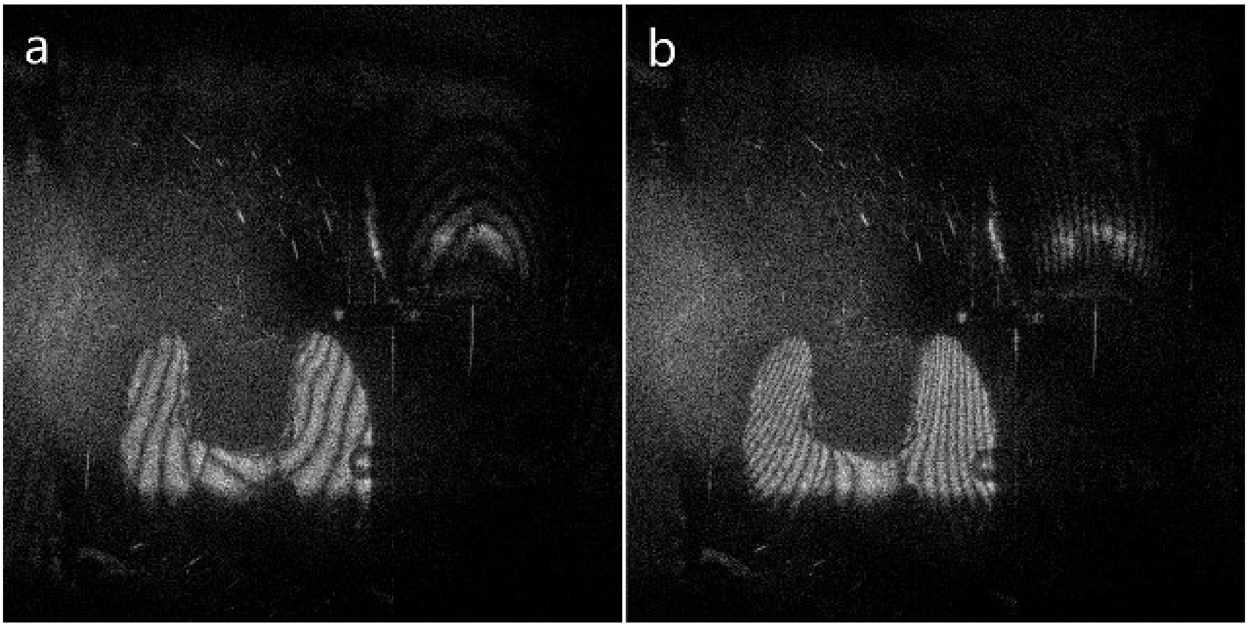

Fig. 2 – Interference pattern in group G1: a) at the end of the curing period (42 sec); b) at the end of the whole examined period (320 sec).

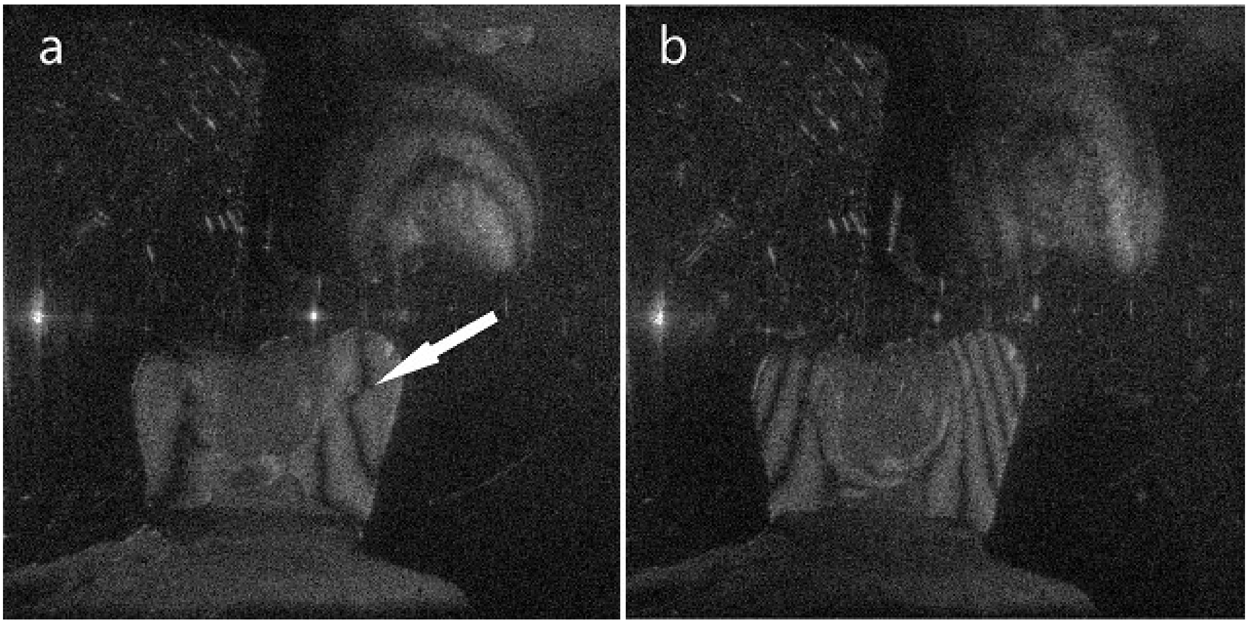

Fig. 3 – Interference pattern in group G2: a) at the end of the curing period (42 sec) – white arrow indicating the change in fringe appearance; b) at the end of the whole examined period (320 sec).

teeing a highly coherent beam. A digital single-lens reflex camera (Canon® EOS50d, 15.1 megapixels, 4752 × 3168 image size) recorded the resulting holograms (every 2 sec during the first minute and 10 sec afterward until the end of the observation period). The obtained images were transferred to a computer and numerically reconstructed by parallel processing on a graphic card (NVidia® GeForce GTX 1060 6GB) [17].

The holographic experiment was based on the interference between the object beam (scattered from the object) and the reference beam (one that misses both the front and rear side of the object and continues to propagate) generated from the same radiation source. Due to the existing movement of the sample (tooth cusps deflection), the reconstructed holographic interferograms showed a specific interference pattern presented in the form of a series of interference lines (so-called "fringes") whose number, shape, and orientation gave information about the resulting mechanical deformation. The exact amount of deformation was calculated by multiplying the number of fringes that appeared in the examined interval of time with the wavelength of laser light [17].

Statistical analysis

Statistical analysis was performed in Minitab® software (version 19.2020.1; 64-bit) using the Student's *t*-test for independent samples (n = 6 + n = 6, G1 and G2, respectively) for testing the presumed hypothesis. The distribution normality of the results was analyzed by the Anderson-Darling tests. Power calculations were carried out for the Student's *t*-test. An alpha level of 0.05 was used for all statistical tests.

Results

The resulting DHI images (interferograms) from both groups presented a specific interference pattern indicating tooth cusps deflection, with each fringe appearing corresponding to deformation of 0.532 µm (Figures 2a–3b). At the end of the examined period, the G1 group samples restored with the cover glass [n = 6; Mean (M) = 5.4; Standard deviation (SD) = 1.6] showed a significantly higher amount of cusps deflection per cusp [t (10) = 4,7; p = 0.001] than the samples from the G2 group restored without it (n = 6; M = 2.1; SD = 0.6).

Table 1 summarizes the measured single values of cusps deflection. The cusps deflection reached a maximum of 7.8 µm and 2.7 µm per cusp in the groups G1 and G2, respectively (Figure 4). The Anderson-Darling test showed that data from both the G1 (AD = 0.2; p = 0.6) and G2 groups (AD = 0.3; p = 0.4) followed a normal distribution. Power calculations, carried out for the Student's *t*-test, showed that the chosen sample size allowed registering differences between groups at < 3 µm (2.9 µm) with the power of 0.87 (87%).

The results also provided qualitative information about the submicron movements of the examined samples – during the curing reaction of the RDM in some samples from the group G2, a change in fringe appearance was noticed when moving along the DEJ projection (Figure 3a).

Discussion

The results of this study contributed to the investigation of the biomechanics of tooth cusps displacement in class II adhesive restorations during PSS development. Utilizing DHI, direct measurement of submicron tooth cusps dis-

Table 1

Measured single values for each tooth cusp, at the end of the whole examined period (final tooth cusps deflection)

	Sample number	Tooth cusp	Final cusps deflection (µm)	Standard deviation (SD)	Sample size (n)
First group (G1)	1	Buccal	4.79	1.6	6
		Palatal	3.72		
	2	Buccal	5.85		
		Palatal	3.72		
	3	Buccal	7.80		
		Palatal	6.39		
Second group (G2)	4	Buccal	2.66	0.62	6
		Palatal	1.06		
	5	Buccal	1.6		
		Palatal	2.13		
	6	Buccal	2.13		
		Palatal	2.66		

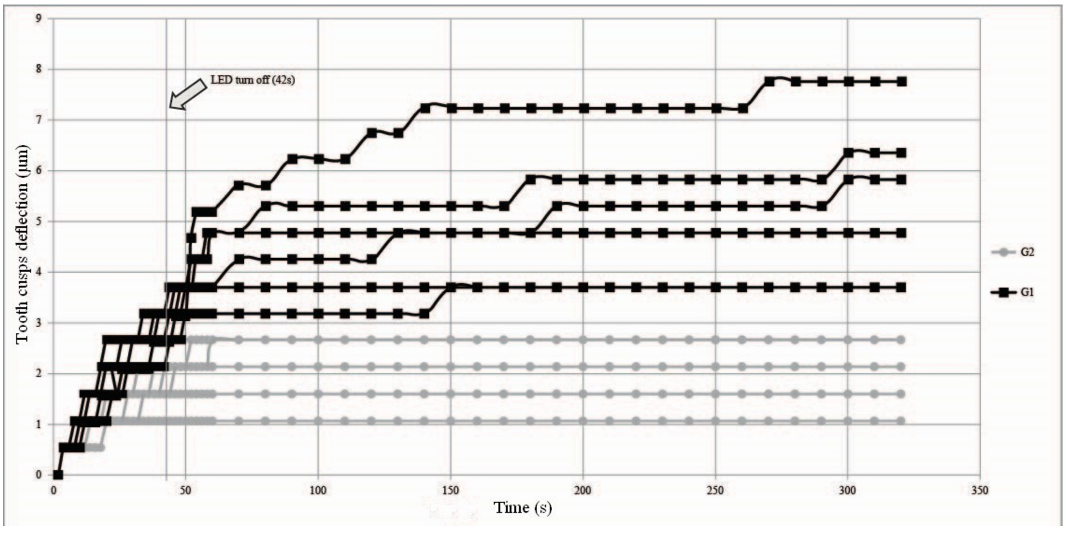

Fig. 4 – Tooth cusps deflection (µm) during the examined period as a function of time. G1 – group 1 samples restored with the additional wall; G2 – group 2 samples restored without the additional wall; LED – light emitting diode.

placement was performed, enabling indirect monitoring of the polymerization reaction kinetics. When the interferograms of the two groups were compared at the same moment of recording (end of the curing period and the whole examined period), it was observed that the interferograms presented more fringes in the G1 group than in the G2 group (Figures 2a–3b). This result indicated increased tooth cusps displacement in the G1 group (on average 5.4 µm per cusp versus 2.1 µm in G2). Assuming the same experimental conditions in the two groups, such as standardized cavities, RDM, restorative technique, and polymerization protocol, the occurrence of increased cusps deflection in the G1 group was associated with the cavity configuration (C-factor) variation due to the presence of an additional glass wall.

The results also showed that cusps deflection did not finish at the end of the curing period but continued to increase in the post-curing period (Figure 4). That indicated that the polymerization reaction continued after the photoactivation step, as already demonstrated by several studies [29–31]. When the post-curing deformation per cusp in the groups G1 and G2 was compared, it was evident that in the group G1, it continued to increase gradually until the end of the examined period, unlike the absence of such progress in the group G2 (Figure 4). Nevertheless, the research conducted by Germscheid et al. [31] stated that examination of the post-curing period of contemporary RDMs should cover a time interval longer than 1 h (up to 15 hrs) due to the significant amount of measured post-curing shrinkage. Further evaluation in a prolonged period could be a topic of another study, using a modified examination protocol by recording the interference images every 10–15 min, thereby rationalizing hard-disk memory storage.

However, the marginal adaption of RDMs in class I and II cavities reflects complex interactions between adhesive bonding on the one hand [25] and PSS at the tooth-restoration interface on the other [32]. The level of PSS and debonding are more probably dependent upon the shape and hence constraints of the cavity [8, 9, 33, 34], as well as viscoelastic properties of RDMs [35, 36] than other factors. It is well known that cavity configuration (C-factor) is one of the main factors affecting the development of PSS [8, 9, 33, 37] since greater confinement imposed on the RDM leaves a smaller number of free surfaces for resin composite shrinkage and PSS relaxation. According to the study of Han et al. [8], the RDMs can shrink relatively freely in a cavity with a larger number of unbonded surfaces. These findings have been shown using different tools in several studies where post-gel PSS was evaluated [9, 38–40], not only tooth cusps displacement. Apart from the effect of the C-factor and RDM elastic modulus upon PSS, a relevant role was also found in adhesive filling techniques [13, 28, 41]. In the present study, a bulk-filling technique was used to avoid sample movement during the examination and preserve the mechanical stability of the setup necessary for the holographic experiment.

Even though the samples in the G1 group were not bonded to the cover glass, this additional wall transformed their cavity configuration, which increased and extended cusps deflection (following PSS), imitating class I cavity configuration [42, 43]. Control of glass stability was performed manually for every sample in the G1 group before filling the cavity. Based on the presented results, the first null hypothesis, stating that there is no significant difference in tooth cusps deflection at the end of the examined period between the two proposed groups (with and without an additional wall), was rejected.

On the other hand, a qualitative assessment of the resulting interference images revealed the change in fringe appearance at the DEJ projection in some samples from the group G2 during the curing reaction of the RDM (Figure 3a). This finding could highlight the role of DEJ in the accommodation of internal forces such as PSS, as suggested by the results of several studies [16, 22, 23]. However, the presence of a regular interference pattern and the influence of the additional wall, in this sense, are yet to be explored.

Given the aggravating circumstances of conducting a clinical study that would establish a direct link between the phenomenon of PSS with certain clinical outcomes, in vitro studies play a significant role in the field of RDM examination due to the need for constant improvement of materials on the market. Therefore, this study proved that DHI, as a non-destructive method with submicron precision, is able to directly investigate the tooth cusps deformation and predict PSS influence on the behavior of adhesively restored molar teeth.

Conclusion

Based on the obtained results and within the limitations of this study, it was concluded that, by changing cavity configuration, the presence of an additional glass cover wall simulating a dental matrix band, had an influence on increased and prolonged tooth cusps deflection during the polymerization reaction of the RDM. Future perspectives would be to explore if any regular pattern in the behavior of tooth tissue under internal stress, such as PSS, could be found, especially in the presence of an additional matrix band wall.

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R E F E R E N C E S

1. *Meereis CTW, Münchow EA, de Oliveira da Rosa WL, da Silva AF, Piva E.* Polymerization shrinkage stress of resin-based dental materials: A systematic review and meta-analyses of composition strategies. J Mech Behav Biomed Mater 2018; 82: 268–81.
2. *Leprince JG, Palin WM, Hadis MA, Devaux J, Leloup G.* Progress in dimethacrylate-based dental composite technology and curing efficiency. Dent Mater 2013; 29(2): 139–56.
3. *Braga RR, Ballester RY, Ferracane JL.* Factors involved in the development of polymerization shrinkage stress in resin-composites: A systematic review. Dent Mater 2005; 21(10): 962–70.
4. *Soares CJ, Faria-E-Silva AL, Rodrigues MP, Vilela ABF, Pfeifer CS, Tantbirojn D,* et al. Polymerization shrinkage stress of composite resins and resin cements – What do we need to know? Braz Oral Res 2017; 31(Suppl 1): e62.
5. *Fok ASL, Aregawi WA.* The two sides of the C-factor. Dent Mater 2018; 34(4): 649–56.
6. *van Dijken JWV, Pallesen U.* Bulk-filled posterior resin restorations based on stress-decreasing resin technology: a randomized, controlled 6-year evaluation. Eur J Oral Sci 2017; 125(4): 303–9.
7. *Wang Z, Chiang MY.* Correlation between polymerization shrinkage stress and C-factor depends upon cavity compliance. Dent Mater 2016; 32(3): 343–52.
8. *Han SH, Sadr A, Tagami J, Park SH.* Internal adaptation of resin composites at two configurations: Influence of polymerization shrinkage and stress. Dent Mater 2016; 32(9): 1085–94.
9. *Boaro LC, Brandt WC, Meira JB, Rodrigues FP, Palin WM, Braga RR.* Experimental and FE displacement and polymerization stress of bonded restorations as a function of the C-Factor, volume and substrate stiffness. J Dent 2014; 42(2): 140–8.
10. *Ausiello P, Ciaramella S, Garcia-Godoy F, Martorelli M, Sorrentino R, Gloria A.* Stress distribution of bulk-fill resin composite in class II restorations. Am J Dent 2017; 30: 227–32.
11. *Ausiello P, Ciaramella S, Martorelli M, Lanzotti A, Gloria A, Watts DC.* CAD-FE modeling and analysis of class II restorations incorporating resin-composite, glass ionomer and glass ceramic materials. Dent Mater 2017; 33(12): 1456–65.
12. *Campos LMP, Parra DF, Vasconcelos MR, Vaz M, Monteiro J.* DH and ESPI laser interferometry applied to the restoration shrinkage assessment. Radiat Phys Chem 2014; 94: 190–3.
13. *Bicalho AA, Pereira RD, Zanatta RF, Franco SD, Tantbirojn D, Versluis A,* et al. Incremental filling technique and composite material-Part I: Cuspal deformation, bond strength, and physical properties. Oper Dent 2014; 39(2): E71–82.
14. *Vinagre A, Ramos J, Alves S, Messias A, Alberto N, Nogueira R.* Cuspal displacement induced by bulk fill resin composite polymerization: Biomechanical evaluation using fiber bragg grating sensors. Int J Biomater 2016; 2016: 7134283.
15. *Campodonico CE, Tantbirojn D, Olin PS, Versluis A.* Cuspal deflection and depth of cure in resin-based composite restorations filled by using bulk, incremental and transtooth-illumination techniques. J Am Dent Assoc 2011; 142(10): 1176–82.
16. *Xia H, Picart P, Montresor S, Guo R, Li JC, Yusuf Solieman O,* et al. Mechanical behavior of CAD/CAM occlusal ceramic reconstruction assessed by digital color holography. Dent Mater 2018; 34(8): 1222–34.
17. *Pantelić DV, Grujić DŽ, Vasiljević DM.* Single-beam, dual-view digital holographic interferometry for biomechanical strain measurements of biological objects. J Biomed Opt 2014; 19(12): 127005.
18. *Pantelić D, Blažić L, Savić-Šević S, Panić B.* Holographic detection of a tooth structure deformation after dental filling polymerization. J Biomed Opt 2007; 12(2): 024026.
19. *Blažić L, Pantelić D, Savić-Šević S, Murić B, Belić I, Panić B.* Modulated photoactivation of composite restoration: Measurement of cuspal movement using holographic interferometry. Lasers Med Sci 2011; 26: 179–86.
20. *Paturzo M, Pagliarulo V, Bianco V, Memmolo P, Miccio L, Merola F,* et al. Digital Holography, a metrological tool for quantitative analysis: Trends and future applications. Opt Lasers Eng 2018; 104: 32–47.
21. *Marshall SJ, Balooch M, Habelitz S, Balooch G, Gallagher R, Marshall GW.* The dentin - enamel junction - a natural, multilevel interface. J Eur Ceram Soc 2003; 23: 2897–904.
22. *Sui T, Lunt AJG, Baimpas N, Sandholzer MA, Li T, Zeng K,* et al. Understanding nature's residual strain engineering at the human dentine–enamel junction interface. Acta Biomater 2016; 32: 256–63.
23. *Fages M, Slangen P, Raynal J, Corn S, Turzo K, Margerit J,* et al. Comparative mechanical behavior of dentin enamel and dentin ceramic junctions assessed by speckle interferometry (SI). Dent Mater 2012; 28(10): e229–38.
24. *Feilzer AJ, de Gee AJ, Davidson CL.* Setting Stress in Composite Resin in Relation to Configuration of the Restoration. J Dent Res 1987; 66(11): 1636–9.
25. *Ausiello P, Ciaramella S, De Benedictis A, Lanzotti A, Tribst JPM, Watts DC.* The use of different adhesive filling material and mass combinations to restore class II cavities under loading and shrinkage effects: a 3D-FEA. Comput Methods Biomech Biomed Engin 2021; 24(5): 485–95.
26. *Watts DC, Marouf AS, Al-Hindi AM.* Photo-polymerization shrinkage-stress kinetics in resin-composites: Methods development. Dent Mater 2003; 19: 1–11.
27. *Van Ende A, de Munck J, Lise DP, van Meerbeek B.* Bulk-fill composites: A review of the current literature. J Adhes Dent 2017; 19(2): 95–109.
28. *Politi I, McHugh LEJ, Al-Fodeh RS, Fleming GJP.* Modification of the restoration protocol for resin-based composite (RBC) restoratives (conventional and bulk fill) on cuspal movement and microleakage score in molar teeth. Dent Mater 2018; 34(9): 1271–7.
29. *Kaiser C, Price RB.* Effect of time on the post-irradiation curing of six resin-based composites. Dent Mater 2020; 36(8): 1019–27.
30. *Al-Ahdal K, Ilie N, Silikas N, Watts DC.* Polymerization kinetics and impact of post polymerization on the Degree of Conversion of bulk-fill resin-composite at clinically relevant depth. Dent Mater 2015; 31(10): 1207–13.
31. *Germscheid W, de Gorre LG, Sullivan B, O'Neill C, Price RB, Labrie D.* Post-curing in dental resin-based composites. Dent Mater 2018; 34(9): 1367–77.
32. *Kim YJ, Kim R, Ferracane JL, Lee IB.* Influence of the compliance and layering method on the wall deflection of simulated cavities in bulk-fill composite restoration. Oper Dent 2016; 41(6): e183–94.
33. *Ghulman MA.* Effect of cavity configuration (C Factor) on the marginal adaptation of low-shrinking composite: A comparative ex vivo study. Int J Dent 2011; 2011: 159749.
34. *Van Ende A, Mine A, De Munck J, Poitevin A, Van Meerbeek B.* Bonding of low-shrinking composites in high C-factor cavities. J Dent 2012; 40(4): 295–303.
35. *Oglakci B, Kazak M, Donmez N, Dalkilic EE, Koymen SS.* The use of a liner under different bulk-fill resin composites: 3D GAP formation analysis by x-ray micro-computed tomography. J Appl Oral Sci 2019; 28: e20190042.

36. *Suiter EA, Tantbirojn D, Watson LE, Yazdi H, Versluis A.* Elastic modulus maturation effect on shrinkage stress in a primary molar restored with tooth-colored materials. Pediatr Dent 2018; 40(5): 370–4.
37. *Braga RR, Boaro LC, Kuroe T, Azevedo CL, Singer JM.* Influence of cavity dimensions and their derivatives (volume and "C" factor) on shrinkage stress development and microleakage of composite restorations. Dent Mater 2006; 22(9): 818–23.
38. *Al Sunbul H, Silikas N, Watts DC.* Polymerization shrinkage kinetics and shrinkage-stress in dental resin-composites. Dent Mater 2016; 32(8): 998–1006.
39. *Versluis A, Tantbirojn D, Pintado MR, DeLong R, Douglas WH.* Residual shrinkage stress distributions in molars after composite restoration. Dent Mater 2004; 20(6): 554–64.
40. *Dejak B, Młotkowski A.* A comparison of stresses in molar teeth restored with inlays and direct restorations, including polymerization shrinkage of composite resin and tooth loading during mastication. Dent Mater 2015; 31(3): e77–87.
41. *Sarcev IN, Petronijevic BS, Atanackovic TM.* A biomechanical model for a new incremental technique for tooth restoration. Acta Bioeng Biomech 2012; 14(3): 85–91.
42. *Van Ende A, De Munck J, Van Landuyt K, Van Meerbeek B.* Effect of Bulk-filling on the Bonding Efficacy in Occlusal Class I Cavities. J Adhes Dent 2016; 18(2): 119–24.
43. *Ausiello P, Ciaramella S, Di Rienzo A, Lanzotti A, Ventre M, Watts DC.* Adhesive class I restorations in sound molar teeth incorporating combined resin-composite and glass ionomer materials: CAD-FE modeling and analysis. Dent Mater 2019; 35(10): 1514–22.

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