©Operative Dentistry, 2021, **46-5**, 577-588

Change in the Shrinkage Forces of Composite Resins According to Controlled Deflection

I-S Yoo • D Kim • K Kim • S-h Park

Clinical Relevance

Polymerization shrinkage forces and the differences in such forces between composite resins decrease with increasing cuspal deflection. When high deflection is expected, controlling composite volume with a base material or use of a layer filling technique is more practical than trying to choose a composite with low polymerization shrinkage stress.

SUMMARY

The aim of this study was to investigate how the polymerization shrinkage forces of composite resins change with change in deflection. Five composites, SDR (Dentsply Caulk, Milford, DE, USA), EcuSphere-Shape (DMG, Hamburg, Germany), Tetric N-Ceram Bulk Fill (Ivoclar Vivadent, Schaan, Liechtenstein), CLEARFIL AP-X (Kuraray Noritake Dental Inc., Sakazu, Kurashiki, Okayama, Japan), and Filtek Z350 XT (3M Dental Products, St Paul, MN, USA), were tested in this experiment. The polymerization shrinkage forces of the composites were measured using a custom-made tooth-deflection-mimicking device and software (R&B Inc, Daejon, Korea). In all measurements, six modes were tested: maximum-deflection, zero-deflection, and four deflection-controlled modes. For each deflection mode, the shrinkage forces were recorded continuously every 0.1 second for 180 seconds. Polymerization shrinkage and flexural modulus were also measured. Eight specimens of each material were allocated for each test. For each material, six groups of shrinkage force values were compared using one-way ANOVA and Tukey post hoc tests at a 95% confidence level. The polymerization shrinkage force of each material in each of the six deflection modes was analyzed with 95% confidence using one-way ANOVA and Tukey post hoc tests. The relationship between the force measured in the six deflection modes and the linear polymerization shrinkage and flexural modulus was analysed with 95% confidence using Pearson correlation analysis. For each material, the following held true: the shrinkage force was highest in zero-deflection mode, the force decreased as deflection increased, and the smallest force appeared in maximum-deflection mode ($p<0.05$). There was

Il-Sang Yoo, DDS, MS, Department of Conservative Dentistry, School of Dentistry, Yonsei University, Seoul, Republic of Korea

Dohyun Kim, DDS, MS, PhD, Department of Conservative Dentistry and Oral Science Research Center, School of Dentistry, Yonsei University, Seoul, Republic of Korea

Kwangman Kim, PhD, professor, Department of Biomaterial & Bioengineering, Yonsei University, Seoul, Republic of Korea

*Sung-ho Park, DDS, MS, PhD, Professor, Department of Conservative Dentistry, Oral Science Research Center, School of Dentistry, Yonsei University, Seoul, Republic of Korea

*Corresponding author: 50-1 Yonsei-ro, Seodaemun-gu, Seoul, Republic of Korea 03722; e-mail: sunghoopark@yuhs.ac

http://doi.org/10.2341/20-196-L

a high negative correlation between allowable deflection and shrinkage force in all materials.

INTRODUCTION

As a direct restorative material, dental resin composites are widely used for anterior and posterior tooth restoration. However, one of the drawbacks of composites is that internal stress is inevitable due to the nature of vinyl polymerization, which involves reductions in intermolecular dimensions and free volume.[1] Shrinkage stress in composite restorations results from polymerization shrinkage occurring under confinement due to bonding to cavity walls;[2] confined shrinkage causes excessive residual stress that, if in tension, can cause micro-crack initiation and breakage.[3-5] Polymerization shrinkage and contraction stress can cause debonding, marginal gap formation, microleakage, secondary dental caries, post-operative hypersensitivity, and cuspal deflection.[6] More than 1% of polymerization shrinkage is unpreventable despite substantial shrinkage reduction efforts.[5]

Polymerization shrinkage stress in composite resins was first studied as a function of restoration shape by Feiltzer and others.[3] Shape was described with a configuration factor, C, representing the ratio of the restoration's bonded to unbonded (free) surfaces. In that experimental set-up, the shape of the restoration was simulated with cylindrical forms of various dimensions and shrinkage stress was continuously measured. Any axial sample contraction, which occurs due to yielding of the load cell to the shrinkage force, was immediately counteracted and the height of the cylindrical forms was maintained with a feedback mechanism. Under these stiff conditions, polymerization shrinkage stress increased as C-factor increased.

However, Watts and others[4,7] reported that teeth and their cavities display elastic and visco-elastic compliance and that stress should be measured while allowing for minimal but essential compliance. In their nonstiff system, the relationship between polymerization and C-factor is more complex than simply a ratio of bonded to unbonded surfaces. When polymerization stress was measured under nonstiff conditions, both C-factor and resin composite mass were important in the production of shrinkage stress.

Less stress was recorded in a nonstiff system than under stiff conditions due to the stress-relieving effect of allowable displacement.[4,8] In the high-compliance system, polymerization shrinkage stress decreased as C-factor increased. This tendency decreased as system compliance decreased and eventually reversed as higher C-factors increased polymerization shrinkage stress.[9]

It has been reported that placing composites in Class II cavity preparation leads to inward deformation of the cusps.[10] This has been termed cuspal deflection and is the result of the interaction between composite resin polymerization shrinkage stress and cavity wall compliance when the adhesive force between tooth and composite resin is sufficiently strong.[11]

The structural and material factors that affect cuspal deflection are cavity width and depth, thickness of residual dentin,[11,12] polymerization shrinkage of composite resin,[13] and flow and compliance of cured composite and teeth.[13,14] The clinical factors affecting cuspal deflection are use of a liner,[15] filling technique,[11,16] restoration method,[11,17] and light curing method.[18]

Cuspal deflection varies from approximately 10-45 μm depending on measurement method, tooth type, cavity preparation type, and cavity size.[10,11] Even within a prepared cavity, deflection may vary according to remaining tooth structure and location in the cavity preparation. Thus, the relationship between polymerization shrinkage and deflection could have a significant clinical effect.

The purpose of this study was to develop an *in vitro* system that exhibits constant compliance but can also exhibit various deflections, mimicking cuspal deflection of the tooth, and to evaluate the relationship between deflection and polymerization shrinkage force. In our experimental devices, the various amounts of deflection under shrinkage force can be controlled by feedback action.

The null hypotheses were:

1. Polymerization shrinkage force does not change, even if deflection changes.
2. Polymerization shrinkage force does not correlate with amount of polymerization shrinkage or flexural modulus.

METHODS AND MATERIALS

Five brands of light-cured composites were used (Table 1).

Density Measurement

Each sample had a volume of 0.063 cm^3, which was equivalent to a 3 mm (width) x 3 mm (depth) x 7 mm (length) Mesial-Occlusal-Distal (MOD) cavity. Measurements were taken, first, of the density of each material in order to apply the same volume of material, and second, of the mass equivalent to the volume. While pre-polymerization density is more accurate, post-polymerization density was used because flowable type SDR, for which pre-polymerization density is

Table 1: *Restorative Materials Used in This Study and Density Measured*

	Manufacturer	LOT #	Density(g/cm^3)
SDR	Dentsply Caulk, Milford, DE, USA	1511000715	1.976(0.005)
EcuSphere-Shape	DMG, Hamburg, Germany	750594	2.039(0.003)
Tetric N-Ceram Bulk Fill	Ivoclar Vivadent, Schaan, Liechtenstein	S14902	2.072(0.028)
CLEARFIL AP-X	Kuraray Noritake Dental Inc., Sakazu, Kurashiki, Okayama, Japan	4J0073	2.332(0.016)
Filtek Z350 XT	3M Dental Products, St Paul, MN, USA	N678112	1.915(0.008)

Abbreviation: g/cm^2 = grams per square centimeter.

hard to measure, was included as one of the samples. The density of five specimens of each material was measured using disks 1 cm in diameter and 1 mm thick. Excellence XS Precision Balances (XS105, Mettler-Toledo International Inc, Greifensee, Switzerland) with Mettler Toledo installed Density Accessory Kits were used in a laboratory environment. Specimen weights were measured on the pan in both air and distilled water. Density, calculated according to the Archimedes principle, was recorded and average values determined. The measured density values are given in Table 1.

Polymerization Shrinkage Force Measurement and Deflection Control

The polymerization shrinkage forces of the resin composites were measured using a custom-made shrinkage force-feedback machine (Figure 1). The polymerization shrinkage force of composites and the control of the accompanying movement of the device used a feedback mechanism (R&B Inc., Daejon, Korea). The instrument was driven by a motor and was designed to move a metal bar up and down. An acrylic rod was screwed into the metal rod. A sensor (Figure 1B) was installed to control the movement of the metal and acrylic rods (Figure 1C, D) by a feedback mechanism. Before placing the composite in the device, the surface of the acrylic rod was roughened with sandpaper (180 grit), treated with adhesive resin (bonding agent, Adhese 2, Ivoclar Vivadent), and light cured. A restorative material (0.063 cm^3) was placed at the end of the acrylic rod. Its position was then adjusted with the motor connected to the metal bar until the thickness of the restorative material reached 2 mm (diameter: 6.4 mm, C-factor = 1.6). The force between the acrylic rod and the resin composite was set to zero using the software, and the resin composite was light cured (Bluephase, Ivoclar Vivadent, 800 mW/cm^2) for 20 seconds through the transparent acrylic base (Figure 1F). The polymerization shrinkage force was measured with a force cell (100 kilogram force [kgf]) connected to the bar, while the displacement of the rod was simultaneously recorded by a sensor with a resolution of 0.1 µm. Measurements were made every 0.1 second for a total time of 180 seconds. The displacement of the rod was adjusted based on feedback, using the installed software. The compliance of this system was 0.5 µm/N.

In the zero-deflection group (Group 1), when the feedback sensor (Figure 1B) detected more than 0.1 µm

Figure 1. *Device for measurement of polymerization shrinkage force and deflection control. (A): load cell; (B): feedback sensor; (C) metal rod; (D) acrylic rod; (E) space for composite specimen placement; (F) acrylic base; (G) light source.*

of downward movement of the metal and acrylic rods (Figure 1C and 1D) during the polymerization process, the metal and acrylic rods were returned upwards to their original position via the feedback system. Thus, the system returned to its previously set position and the deflection value was 0.

In the maximum-deflection mode (Group 6), polymerization shrinkage force measurements were conducted without any feedback from the rod, and maximum deflection occurred in each composite. Deflection values of 0 and maximal deflection for each composite were measured in groups 1 and 6, respectively, and four intermediate deflection values were allocated to Groups 2, 3, 4, and 5 (Table 2). In these groups, rod deflection was controlled by the feedback system. The measurements were repeated ten times for each group of materials. A schematic of the experimental design is shown in Figure 2.

Measurement of Linear Polymerization Shrinkage

Polymerization shrinkage was measured using a custom-made Linometer (R&B Inc, Daejon, Korea) following the procedures previously described by Kim and Park.[19] Resin specimens in equal amounts were prepared by applying composite resin to a cylindrical mold with a diameter of 4.5 mm and a depth of 1.3 mm. The resin specimens were placed on the metal disk of a custom-made Linometer (R&B) and covered with a glass slide; the metal disk and the glass slide were covered with a thin coating of glycerin gel to prevent adhesion. An LED-type light-curing unit (Bluephase, Ivoclar Vivadent, 800 mW/cm^2) was placed 1 mm above the glass slide, and the material was light cured for 20 seconds. As the light irradiation progressed, the composite resin shrank in the direction of the light, and the metal disk moved together with the composite resin; the measured value of this movement was recorded by computer. Polymerization shrinkage was measured for 120 seconds from the start of light irradiation eight times.

Measurement of Flexural Modulus

This test was carried out in accordance with ISO 4049. Specimens 2 ± 0.1 × 2 ± 0.1 × 25 ± 2.0 mm in size were prepared. Each specimen was light cured along its length using a light-curing unit (Bluephase N, 800 mW/cm^2) for three 20-second exposures. If there were bubbles, voids, or other defects on the surface, a new specimen was made. The specimens were stored for 24 ± 1 hours in distilled water at 37 ± 1°C until the test. The size (width, height) of the specimen was measured with internal and external calipers, and the specimens were wet ground slightly with 320-grit silicon carbide paper on all four surfaces to reduce flash. Maximum load and maximum deflection were measured with a three-point bending test at a crosshead speed of 0.75 ± 0.25 mm/minute on a universal testing machine (Instron 3366, Norwood, MA, USA). After the measurement, flexural moduli were calculated in gigapascals (GPa) using the following equation:

$$E_{flexural} = \frac{FL^3}{4wdh^3}$$

where $E_{flexural}$ = flexural modulus, F = maximum load, L = span length, w = specimen width, h = specimen height, and d = deflection.

Statistical Analysis

For each material, shrinkage force values of the six groups were compared using one-way ANOVA and Tukey *post hoc* tests at a 95% confidence level. One-dimensional linear regression analyses were performed to explore the relationship between polymerization shrinkage force and deflection in each material. Pearson correlation analyses were done with 95% confidence to evaluate the relationship between polymerization

Table 2: *Mean (SD) of Polymerization Shrinkage Force (kgf)a*

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
SDR	6.5 (0.8) Cd	4.7 (0.6) BCc	4.3 (0.5) BCbc	4.1 (0.6) Cbc	3.6 (0.7) Cab	3.0 (0.3) Ba
EcuSphere-Shape	6.1 (0.5) Ce	4.9 (0.7) Cd	4.4 (0.8) Ccd	4.0 (0.6) BCbc	3.4 (0.8) BCab	2.7 (0.2) Ba
Tetric N-Ceram Bulk Fill	4.4 (0.6) ABd	3.9 (0.6) Acd	3.7 (0.6) ABc	3.2 (0.7) Abc	2.7 (0.6) ABab	2.0 (0.2) Aa
CLEAR -FIL AP-X	4.7 (0.2) Be	4.1 (0.5) ABd	3.6 (0.4) ABcd	3.3 (0.8) ABbc	2.8 (0.5) ABCb	1.9 (0.3) Aa
Filtek Z350 XT	3.9 (0.7) Aa	3.5 (0.5) Abc	3.1 (0.5) Ab	3.0 (0.4) Ab	2.2 (0.6) Aa	1.8 (0.2) Aa

[a] Groups with distinct uppercase letters exhibit statistically significant differences in each column and those with distinct lowercase letters exhibit statistically significant differences in each row ($p<0.05$).
Abbreviations: SD = standard deviation; kgf = kilogram force.

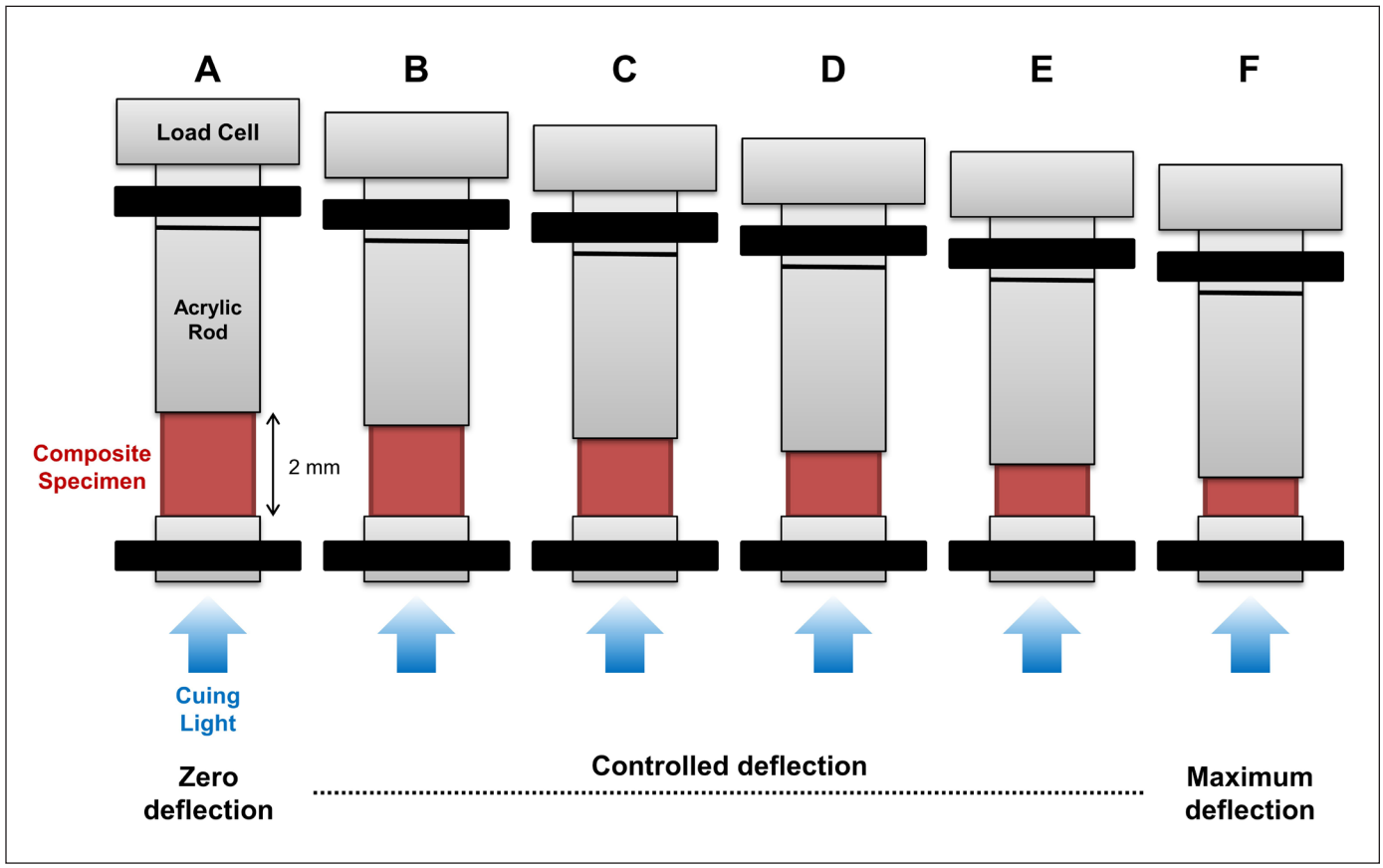

Figure 2. *Polymerization shrinkage force with various deflections. (A): zero deflection; (B-E): controlled deflection; (F): maximum deflection.*

shrinkage force and linear polymerization shrinkage of the materials in each group, between polymerization shrinkage force and flexural modulus of the materials in each group, and between linear polymerization shrinkage and flexural modulus of the materials. Statistical analyses were conducted using PASW statistics 18 software (SPSS for Windows: SPSS Inc, Chicago, IL, USA).

RESULTS

For the SDR material, when the deflection increased from 0 μm to 14.3 μm, the polymerization shrinkage force decreased from 6.5 kgf to 3.0 kgf (Figure 3A, Table 2). There were statistically significant differences in the shrinkage force value between the groups (p<0.05, Table 2). An equation of y = -0.2229x + 6.3686 (R^2=0.9082) was acquired via regression analysis to express the relationship between polymerization force and deflection value (Figure 4A).

For the EcuSphere-Shape material, when the system displacement increased from 0 μm to 14.4 μm, the polymerization shrinkage force decreased from 6.06 kgf to 2.73 kgf (Figure 3B, Table 2). There were statistically significant differences in the shrinkage force value between the groups (p<0.05, Table 2). An equation of y = -0.2435x + 6.8696 (R^2=0.8501) was acquired via regression analysis to express the relationship between polymerization force and deflection value (Figure 4B).

For the Tetric N-Ceram Bulk Fill material, when the system displacement increased from 0 μm to 10.2 μm, the polymerization shrinkage force decreased from 4.44 kgf to 2.00 kgf (Figure 3C, Table 2). There were statistically significant differences in the shrinkage force value between the groups (p<0.05, Table 2). An equation of y = -0.2116x + 4.7669 (R^2=0.7525) was acquired via regression analysis to express the relationship between polymerization force and deflection value (Figure 4C).

For the CLEARFIL AP-X material, when the system displacement increased from 0 μm to 10.2 μm, the polymerization shrinkage force decreased from 4.73 kgf to 1.94 kgf (Figure 3D, Table 2). There were statistically significant differences in the shrinkage force value between the groups (p<0.05, Table 2). An equation of y = -0.287x + 5.6857 (R^2=0.8438) was acquired via regression analysis to express the relationship between polymerization force and deflection value (Figure 4D).

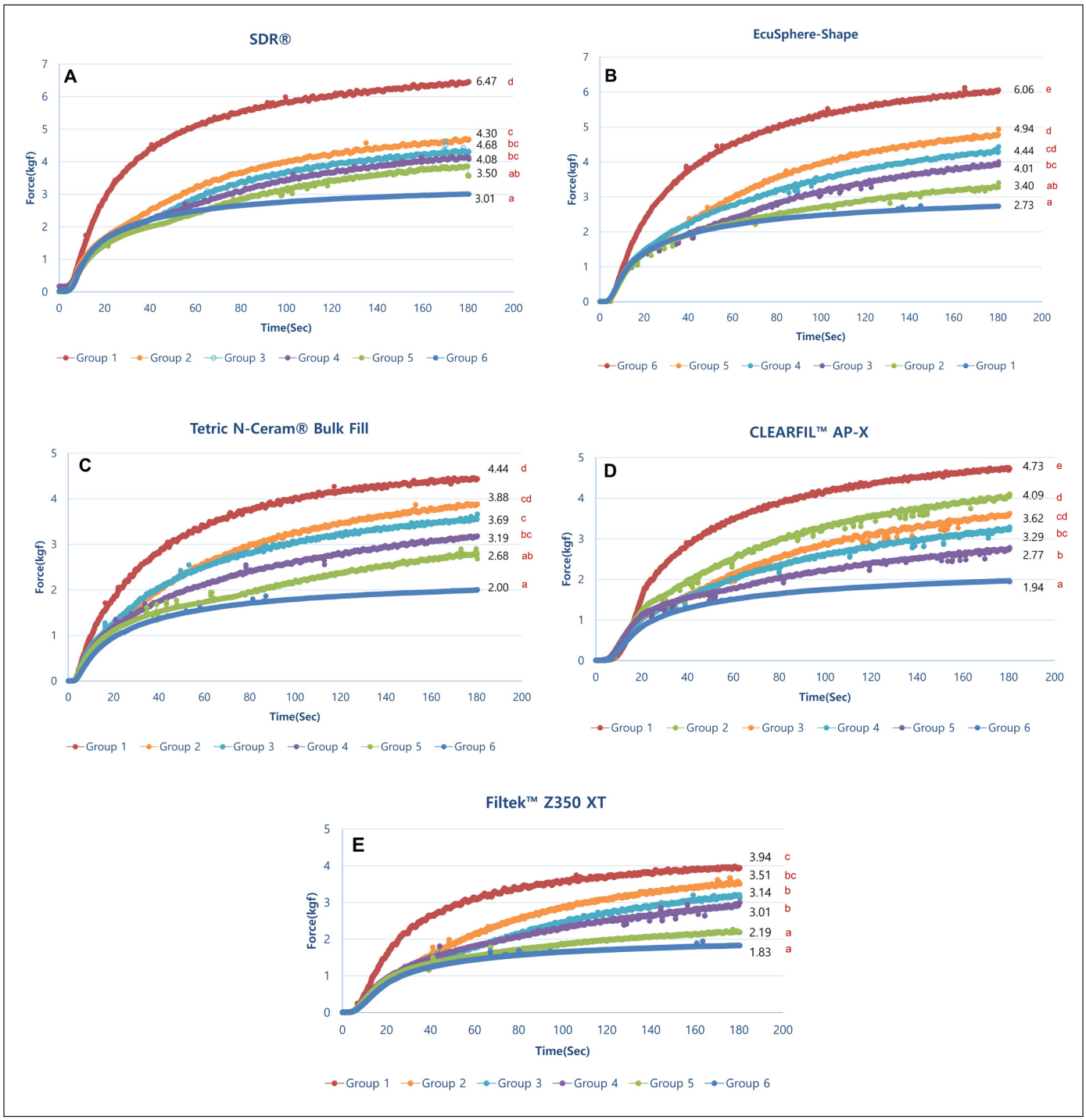

Figure 3. *Time vs force graphs for all composites. (A): SDR; (B): EcuSphere-Shape; (C): Tetric N-Ceram Bulk Fill; (D): CLEARFIL AP-X; (E): Filtek Z350 XT. a Different letters represent statistically significant differences.*

For the Filtek Z350 XT material, when the system displacement increased from 0 µm to 10 µm, the polymerization shrinkage force decreased from 3.94 kgf to 1.83 kgf (Figure 3E, Table 2). There were statistically significant differences in the shrinkage force value between the groups (p<0.05, Table 2). An equation of y = -0.1675x + 4.0691 (R^2=0.7397) was acquired via regression analysis to express the relationship between polymerization force and deflection value (Figure 4E).

There were significant differences in polymerization shrinkage forces between materials in each group (Table 2). There were also significant differences in

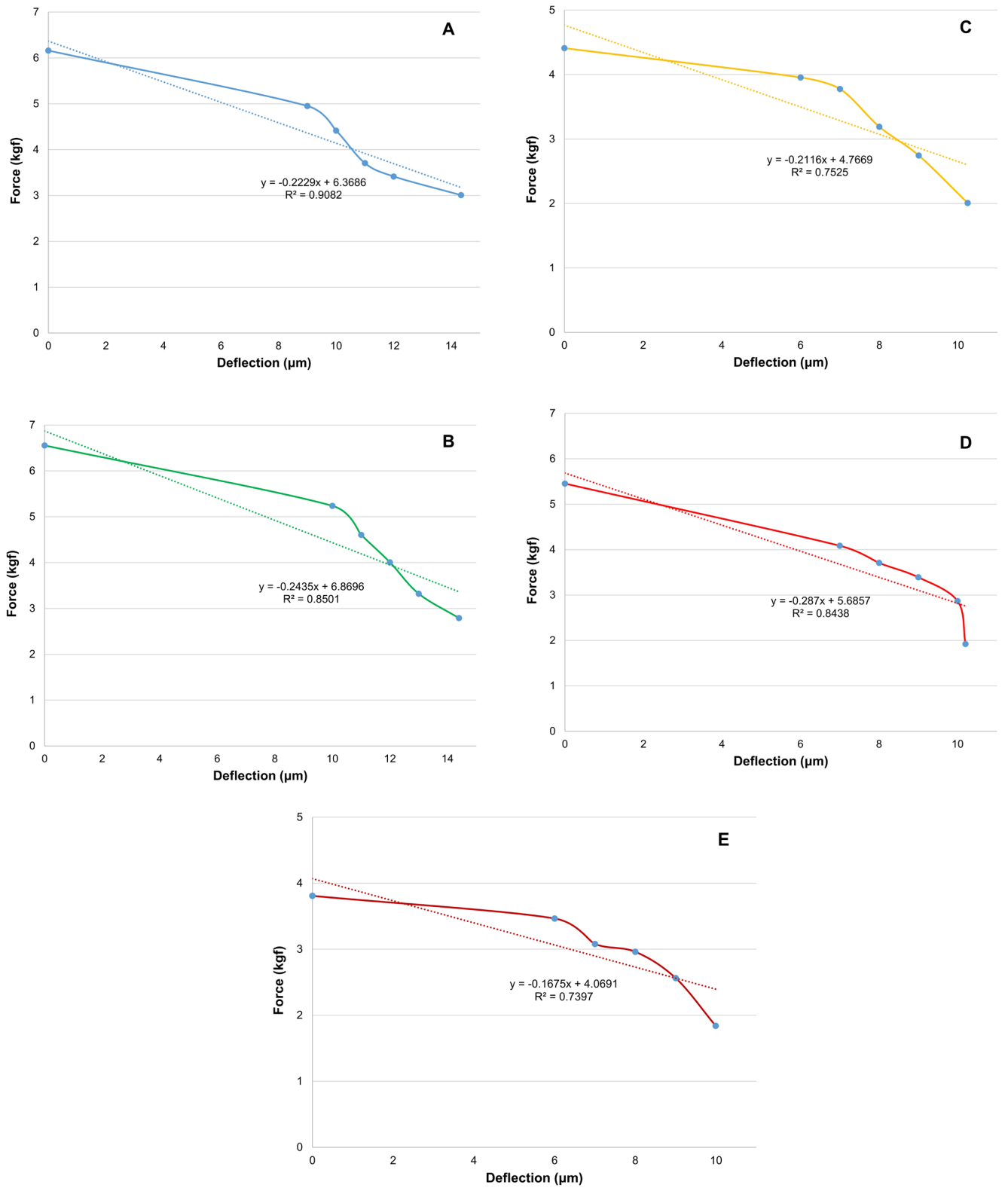

Figure 4. *Deflection vs force graphs with regression analysis. (A): SDR; (B): EcuSphere-Shape; (C): Tetric N-Ceram Bulk Fill; (D): CLEARFIL AP-X; (E): Filtek Z350 XT.*

linear polymerization shrinkage and flexural modulus between materials ($p<0.05$) (Table 3). The Pearson product-moment correlation coefficients between the polymerization shrinkage force and the linear polymerization shrinkage in each group ranged from 0.641 (Group 4) to 0.925 (Group 6). The Pearson product-moment correlation coefficients between the polymerization shrinkage force and flexural modulus ranged from -0.444 (Group 5) to -0.776 (Group 6) (Table 4). The Pearson product-moment correlation coefficient between linear polymerization shrinkage and flexural modulus was -0.848 ($p<0.001$).

DISCUSSION

Polymerization shrinkage of composite resin causes problems such as cuspal deflection,[10,20-23] interferes with marginal and internal adaptation of composite restorations to tooth substance,[24-27] and remains as a tensile residual force on the tooth, potentially lowering tooth fatigue strength.[28,29] Initially high external and internal adaptations are exacerbated after undergoing fatiguing processes, such as simulated chewing and thermocycling, due to the residual forces on the composite resin. In addition, the degree of marginal and internal adaptations is related to the amount and degree of polymerization shrinkage.[24,26,27,30,31]

According to Watts and Satterthwaite,[7] the polymerization stress depends on both C-factor and composite mass in a compliance-allowed system. The volume of composite used in the present study was 0.063 cm^3, which was chosen to simulate Lee and Park's study[10] as much as possible. The C-factor, which was 1.6, was set to simulate that of their MOD cavity as much as possible. In their study, the cuspal deflection in the premolar MOD cavity was 14.6-22.7 μm. In the present study, deflection ranged up to 15 μm, so the two studies are consistent.

Table 3: *Mean (SD) of Polymerization Shrinkage (μm), Flexural Modulus (GPa)*

	Linear Polymerization Shrinkage	Flexural Modulus
SDR	31.6 (2.3) e	1.9 (0.1) a
EcuSphere-Shape	22.2 (0.7) d	3.2 (0.1) b
Tetric N-Ceram Bulk Fill	16.1 (1.5) c	5.8 (0.2) c
CLEAR -FIL AP-X	9.6 (0.8) a	13.3 (0.6) e
Filtek Z350 XT	11.6 (0.8) b	7.0 (0.3) d

Abbreviations: SD = standard deviation; μm = micrometer; GPa = gigapascal.

Table 4: *Pearson Correlations (Significance) Between the Force Measured in the Six Deflection Modes and the Linear Polymerization Shrinkage and Flexural Modulus*

Polymerization Shrinkage Force	Linear Polymerization Shrinkage	Flexural Modulus
Group 1	0.908 (0.000)	-0.642 (0.000)
Group 2	0.775 (0.000)	-0.605 (0.000)
Group 3	0.773 (0.000)	-0.514 (0.001)
Group 4	0.641 (0.000)	-0.449 (0.004)
Group 5	0.649 (0.000)	-0.444 (0.004)
Group 6	0.925 (0.000)	-0.776 (0.000)

The deflections and polymerization shrinkage forces were highly negatively correlated in all materials (Figure 4), and the first null hypothesis is rejected. With lower deflection, the system was stiffer, causing more force due to difficulties in polymerization shrinkage. On the other hand, with higher deflection, the system was more flexible, and it accommodated some of the polymerization shrinkage, thus reducing the relative force.

In this experiment, the polymerization shrinkage force and linear polymerization shrinkage were positively correlated to a moderate-to-high degree in all groups (Table 4). The Pearson correlation coefficients between the polymerization shrinkage force and the flexural modulus in each group were in a moderate range, between -0.444 and -0.776 (Table 4). Thus, the second null hypothesis is rejected.

The present study showed that deflection is highly negatively correlated with polymerization shrinkage force (Figure 4) and the polymerization shrinkage force is highly correlated with the amount of polymerization shrinkage (Table 4). This is consistent with a previous study in which the amount of polymerization shrinkage and cuspal deflection were highly correlated.[10]

The results of this study showed that linear polymerization shrinkage had a stronger effect on polymerization shrinkage force than flexural modulus in all groups (Table 4). Polymerization shrinkage itself is the fundamental cause of the polymerization shrinkage force. Flexural modulus, on the other hand, limits the proportion of the polymerization shrinkage force that is generated by polymerization shrinkage. Thus, although linear polymerization shrinkage and flexural modulus affect shrinkage force, the amount of shrinkage itself seems to be more influential in all

groups. This is consistent with a previous study by Kim and Park,[21] in which a moderate correlation was found between flexural modulus and cuspal deflection. However, Tsujimoto and others reported that no significant relationship was found between the two.[23] The differences may be attributable to differences in the materials used. In the present study, the Pearson correlation coefficient between polymerization shrinkage and elastic modulus was -0.848. The high negative correlation between the two may have affected polymerization shrinkage force and deflection and resulted in a moderate correlation between flexural modulus and cuspal deflection.

As for the relationship between C-factor, polymerization shrinkage, and internal adaptation, Han and others[32] reported that internal adaptation in a high–C-factor cavity is inferior to that in a low–C-factor cavity for both conventional and bulk-filled composites; furthermore, polymerization stress under the compliance-allowed condition (Group 6 in the present study) was significantly correlated with internal adaptation in both high– and low–C-factor cavities. The difference in polymerization shrinkage force between materials was greater in zero-deflection mode (Group 1) and had a decreasing tendency as deflection increased (Figure 5, Table 2). The results of both the present study and the study by Han and others imply that it is important to choose composites with lower polymerization shrinkage force in clinical situations with high C-factors and/or lower deflection values, such as Class I and V cavities. On the other hand, the choice of materials is less important in higher deflection situations such as in Class II cavities. Application of a clinical technique that reduces polymerization shrinkage, such as reducing the amount of composite used with a base[33] or a proper layering technique,[21,34,35] is more important in such cases.

In a class II cavity, deflection of the tooth differs according to location and remaining tooth structure. The deflection of the cusp tip area is higher than that of the gingival or pulpal wall area. Considering the results of the present study, the polymerization shrinkage force would be lower at the cusp tip than in the pulpal or gingival wall area, and internal adaptation would differ between the areas. The study by Han and Park,[36] in which the internal adaptation of a class II cavity was

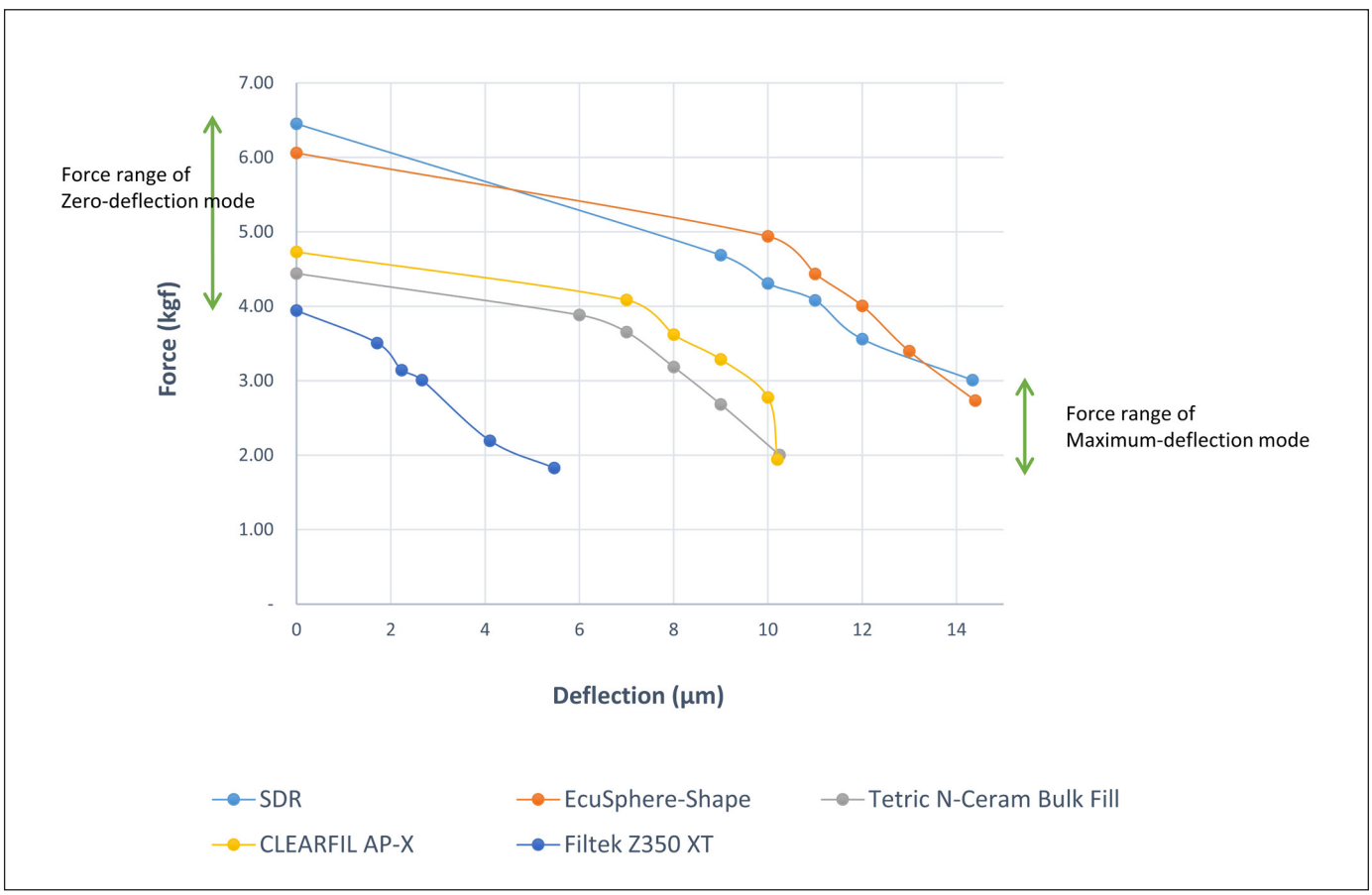

Figure 5. *Deflection vs force curves for all composites.*

evaluated using micro-CT, supports this assumption. In that study, the gingival floor of the proximal box and the pulpal floor of the cavity preparation had higher imperfect margins than did the buccal and lingual walls of the proximal box.

Considering the results of the present study, care should be taken when composites are placed on the pulpal floor, where deflection would be limited. According to Han and others,[37] placing an intermediate layer between the pulpal floor and the composite material as a base or lining material increases the internal adaptation of a restoration by decreasing polymerization shrinkage stress. When flowable composites are considered to line a cavity floor, materials with low polymerization shrinkage stress should be chosen because of the stress's effect on internal adaptation.[37] In class II cavities, after placement of the intermediate layer, the importance of selecting materials with low polymerization shrinkage stress would be reduced; in such cases the composite is placed over the intermediate layer, which allows more deflection than the pulpal or gingival floor, and the differences in polymerization shrinkage between materials will be reduced. A proper layering technique would be more beneficial in this situation.[21,34,35]

SDR, a flowable-type bulk fill composite, showed the same or higher polymerization shrinkage force than other packable or packable-type bulk fill composites in all groups. This finding is consistent with previous studies that compared the polymerization shrinkage stress of bulk fill and packable composites.[19,34,38] However, the polymerization shrinkage stress of SDR was relatively low in previous studies when compared with that of other flowables or flowable-type bulk fill materials.[34,37,38] In this sense, SDR could be recommended as an intermediate material compared to other flowables.

CONCLUSION

For each material, the shrinkage force was the highest in zero-deflection mode, the force decreased as deflection increased, and the smallest force appeared in maximum-deflection mode. There was a high negative correlation between allowable deflection and shrinkage force in all materials.

(Accepted 27 November 2020)

Acknowledgements

This study was supported by Yonsei University College of Dentistry Research Fund 6- 2019-0015

Conflict of Interest

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

REFERENCES

1. Ferracane JL & Hilton TJ (2016) Polymerization stress--Is it clinically meaningful? *Dental Materials* **32(1)** 1-10.
2. Braga RR, Ballester RY, & Ferracane JL (2005) Factors involved in the development of polymerization shrinkage stress in resin-composites: A systematic review *Dental Materials* **21(10)** 962-970.
3. Feilzer AJ, De Gee AJ, & Davidson CL (1987) Setting stress in composite resin in relation to configuration of the restoration *Journal of Dental Research* **66(11)** 1636-1639.
4. Watts DC, Marouf AS, & Al-Hindi AM (2003) Photo-polymerization shrinkage-stress kinetics in resin-composites: Methods development *Dental Materials* **19(1)** 1-11.
5. Weinmann W, Thalacker C, & Guggenberger R (2005) Siloranes in dental composites *Dental Materials* **21(1)** 68-74.
6. Schneider LF, Cavalcante L, & Silikas N (2010) Shrinkage stresses generated during resin-composite applications: A review *Journal of Dental Biomechanics* **2010**. Published online 2009 Sep 30. doi: 10.4061/2010/131630
7. Watts DC & Satterthwaite JD (2008) Axial shrinkage-stress depends upon both C-factor and composite mass *Dental Materials* **24(1)** 1-8.
8. Lu H, Stansbury JW, Dickens SH, Eichmiller FC, & Bowman CN (2004) Probing the origins and control of shrinkage stress in dental resin-composites: I. Shrinkage stress characterization technique *Journal of Materials Science: Materials in Medicine* **15(10)** 1097-1103.
9. Wang Z & Chiang MYM (2016) Correlation between polymerization shrinkage stress and C-factor depends upon cavity compliance *Dental Materials* **32(3)** 343-352.
10. Lee SY & Park SH (2006) Correlation between the amount of linear polymerization shrinkage and cuspal deflection *Operative Dentistry* **31(3)** 364-370.
11. 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.
12. Meredith N & Setchell DJ (1997) In vitro measurement of cuspal strain and displacement in composite restored teeth *Journal of Dentistry* **25(3)** 331-337.
13. Suliman AA, Boyer DB, & Lakes RS (1993) Interferometric measurements of cusp deformation of teeth restored with composites *Journal of Dental Research* **72(11)** 1532-1536.
14. Davidson CL & De Gee AJ (1984) Relaxation of polymerization contraction stresses by flow in dental composites *Journal of Dental Research* **63(2)** 146-148.
15. Unterbrink GL & Liebenberg WH (1999) Flowable resin

composites as "filled adhesives": literature review ard clinical recommendations *Quintessence International* **30(4)** 249-257.

16. Rees JS, Jagger DC, Williams DR, Brown G, & Duguid W (2004) A reappraisal of the incremental packing technique for light cured composite resins *Journal of Oral Rehabilitation* **31(1)** 81-84.
17. Rees JS & Jacobsen PH (1992) Stresses generated by luting resins during cementation of composite and ceramic inlays *Journal of Oral Rehabilitation* **19(2)** 115-122.
18. Ericson D, Paulsson L, Sowiak H, & Dérand T (1994) Reduction of cusp deflection resulting from composite polymerization shrinkage, using a light-transmitting cone *Scandinavian Journal of Dental Research* **102(4)** 244-248.
19. Kim HJ & Park SH (2014) Measurement of the internal adaptation of resin composites using micro-CT and its correlation with polymerization shrinkage *Operative Dentistry* **39(2)** E57-70.
20. Andreasi Bassi M, Serra S, Andrisani C, Lico S, Baggi L, & Lauritano D (2016) Polymerization shrinkage and spherical glass mega fillers: Effects on cuspal deflection *Journal of Oral Implantology (Rome)* **9(Suppl 1-2016 to N 4-2016)** 71-79.
21. Kim ME & Park SH (2011) Comparison of premolar cuspal deflection in bulk or in incremental composite restoration methods *Operative Dentistry* **36(3)** 326-334.
22. Prager M, Pierce M, Atria PJ, Sampaio C, Cáceres E, Wolff M, Giannini M, & Hirata R (2018) Assessment of cuspal deflection and volumetric shrinkage of different bulk fill composites using non-contact phase microscopy and micro-computed tomography *Dental Materials* **37(3)** 393-399.
23. 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.
24. Han S-H, Sadr A, Tagami J, & Park S-H (2016) Internal adaptation of resin composites at two configurations: Influence of polymerization shrinkage and stress *Dental Materials* **32(9)** 1085-1094.
25. Han S & Park S (2017) Comparison of internal adaptation in Class II bulk-fill composite restorations using micro-CT *Operative Dentistry* **42(2)** 203-214.
26. Jung JH & Park SH (2017) Comparison of polymerization shrinkage, physical properties, and marginal adaptation of flowable and restorative bulk fill resin-based composites *Operative Dentistry*. **42(4)** 375-386.
27. Kim H & Park S (2014) Measurement of the internal adaptation of resin composites using micro-CT and its correlation with polymerization shrinkage *Operative Dentistry* **39(2)** e57-e70.
28. Bathias C (2006) An engineering point of view about fatigue of polymer matrix composite materials *International Journal of Fatigue* **28(10)** 1094-1099.
29. Ferracane JL (2008) Buonocore Lecture. Placing dental composites--a stressful experience *Operative Dentistry* **33(3)** 247-257.
30. Rocca GT, Gregor L, Sandoval MJ, Krejci I, & Dietschi D (2012) In vitro evaluation of marginal and internal adaptation after occlusal stressing of indirect class II composite restorations with different resinous bases and interface treatments. "Post-fatigue adaptation of indirect composite restorations" *Clinical Oral Investigations* **16(5)** 1385-1393.
31. Dietschi D, Bindi G, Krejci I, & Davidson C (2002) Marginal and internal adaptation of stratified compomer-composite Class II restorations *Operative Dentistry* **27(5)** 500-509.
32. Han SH, Sadr A, Tagami J, & Park SH (2016) Internal adaptation of resin composites at two configurations: Influence of polymerization shrinkage and stress *Dental Materials* **32(9)** 1085-1094.
33. Kwon OH, Kim DH, & Park SH (2010) The influence of elastic modulus of base material on the marginal adaptation of direct composite restoration *Operative Dentistry* **35(4)** 441-447.
34. Jung JH & Park SH (2017) Comparison of polymerization shrinkage, physical properties, and marginal adaptation of flowable and restorative bulk fill resin-based composites *Operative Dentistryt* **42(4)** 375-386.
35. Kwon Y, Ferracane J, & Lee I-B (2012) Effect of layering methods, composite type, and flowable liner on the polymerization shrinkage stress of light cured composites *Dental Materials* **28(7)** 801-809.
36. Han SH & Park SH (2017) Comparison of internal adaptation in Class II bulk-fill composite Restorations Using Micro-CT *Operative Dentistry* **42(2)** 203-214.
37. Han SH, Sadr A, Shimada Y, Tagami J, & Park SH (2019)

Internal adaptation of composite restorations with or without an intermediate layer: Effect of polymerization shrinkage parameters of the layer material *Journal of Dentistry* **80(January)** 41-48.

38. Jang JH, Park SH, & Hwang IN (2015) Polymerization shrinkage and depth of cure of bulk-fill resin composites and highly filled flowable resin *Operative Dentistry* **40(2)** 172-180.