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Relationship Between Simulated Gap Wear and Generalized Wear of Resin Luting Cements

A Tsujimoto • WW Barkmeier • T Takamizawa • MA Latta • M Miayazaki

Clinical Relevance

Gap wear and generalized wear simulation models can be used to assess the wear resistance of resin luting cements. In clinical situations, with restricted light exposure conditions, care should be taken to choose a resin luting cement that can be effectively cured in the chemical-cure mode.

SUMMARY

Objective: The relationship between the simulated gap wear and generalized wear of resin luting cements was investigated.

Methods: Five resin luting cements, G-Cem LinkForce (GL), Multilink Automix (MA), NX3 Nexus, Panavia V5 (PV), and RelyX Ultimate were evaluated and subsequently subjected to a wear challenge in a Leinfelder-Suzuki (Alabama) wear simulation device. Half of the specimens from each resin luting cement were photocured for 40 seconds and the other half were not photo-cured. The simulated gap and generalized wear were generated using a flat-ended stainless steel antagonist. Wear testing was performed in a water slurry of polymethyl methacrylate beads, and the simulated gap and generalized wear were determined using a noncontact profilometer (Proscan 2100) in conjunction with the Proscan and AnSur 3D software.

Results: A strong relationship was found between the gap wear and generalized wear simulation models. The simulated gap wear and generalized wear of the resin luting cements followed similar trends in terms of both volume loss and mean depth of wear facets with each curing method. Unlike the simulated gap wear and generalized wear of GL and PV, those of MA, NX, and RU were influenced by the curing method.

Conclusion: The results of this study indicate that simulated gap wear of resin luting cements is very similar to simulated generalized wear. In most cases, dual curing appears to ensure greater wear resistance of resin luting cements than chemical curing alone. The wear resistance of some resin luting cements appears to be material dependent and is not influenced by the curing method.

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INTRODUCTION

The increasing esthetic demands in clinical dentistry have resulted in the continued development of esthetic restorative materials such as resin composites, glass ceramic and zirconia.[1] These developments include intracoronal and extracoronal restorations which use esthetic restorative materials requiring the use of a luting cement.[2] Several issues associated with the fit and marginal adaptation of esthetic restorations appear to significantly influence their durability.[3] Thus, the selection of a luting cement is an important consideration in determining the long-term clinical success of esthetic restorations.[4] The stability of such restorations has been increased using a resin luting cement with high mechanical and low solubility properties.[5] Despite their improved physical properties, interfacial and/or marginal defects have been clinically observed to occur frequently around bonded esthetic restorations.[6] This is particularly important for inlay and onlay restorations of posterior teeth, where the cement margin is exposed on the occlusal surface. Therefore, good physical properties (eg, surface hardness and wear resistance) are required for resin luting cements.[7] Although the wear resistance of esthetic restorative materials have been extensively examined, limited research has been reported in the area of resin luting cements.

In a previous study, Shinkai and others[8] examined the wear resistance of different types of resin luting cements and a glass ionomer cement in terms of marginal gap formation. A resin luting cement with micro fillers was found to provide the greatest wear resistance, whereas a glass ionomer cement exhibited the lowest wear resistance. In addition, these investigators reported significant relationships among the gap width, amount of wear, and type of cement. Furthermore, Kawai and others[9] examined the relationship between the gap wear and the filler particle size of a resin luting cement and found a strong relationship (R^2>0.9) between the vertical wear loss and the gap width for the three resin luting cements examined in their study. They also found that a resin luting cement having submicron fillers offered greater wear resistance when compared with those including hybrid fillers.

One of the primary areas of concern when developing luting cements is noncontact generalized wear or erosion.[10] Noncontact generalized erosion is one of the common wear mechanisms responsible for the interfacial and/or marginal breakdown of a luting cement. Whereas the intrinsic wear of a luting cement is important, interfacial and/or marginal gap wear is also a critical concern. Gap wear is influenced by both material properties and the unique environment of the cement.[11] With the objective of evaluating the potential loss of luting cements at the interface, a new model was developed for gap wear simulation. This model uses a thin gap (300 μm wide, 3 mm long) in a stainless steel custom fixture.

The purpose of this laboratory study was to evaluate the relationship between the simulated gap wear and generalized wear of resin luting cements. The null hypotheses to be tested were that 1) there would be no relationship between the simulated gap wear and generalized wear of resin luting cements; and 2) the simulated gap wear and generalized wear of resin luting cements would not be influenced by the type of material or curing method.

METHODS AND MATERIALS

Study Materials

Five resin luting cements were evaluated in this study: G-Cem LinkForce (GL; GC, Tokyo, Japan); Multilink Automix (MA; Ivoclar Vivadent, Schaan, Lichtenstein); NX3 Nexus (NX; Kerr, Orange, CA, USA); Panavia V5 (PV; Kuraray Noritake Dental, Tokyo, Japan); and RelyX Ultimate (RU; 3M ESPE, St Paul, MN, USA). The resin luting cements used in this study are listed in Table 1 along with their associated lot numbers, components, and percentages of filler loading, which were provided by the manufacturers.

Specimen Preparation for Simulated Gap Wear

A total of 40 wear specimens were prepared for each of the five resin luting cements for simulated gap wear testing. A stainless steel custom fixture was designed to examine the resin luting cement wear, with a thin gap for simulated gap wear testing. The two-piece fixture was designed to have a gap (300 μm wide, 3 mm long, and 4 mm deep) for simulated gap wear testing. Half the specimens (20 specimens, designated as the dual-cure group) of each resin luting cement were photo-cured for 40 seconds at a standardized distance of 2 mm with a quartz-tungsten halogen unit (Spectrum 800 Curing Unit, Dentsply Caulk, Milford, DE, USA) set at 600 mW/cm^2. The other half (20 specimens, designated as the chemical-cure group) were not photo-cured. After 24 hours, the cement surfaces were polished flat to 4000 grit using a sequence of silicon carbide papers (Struers, Cleveland, OH, USA) and a grinder-polisher (Ecomet 4, Buehler, Lake Bluff, IL, USA).

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Table 1: *Resin Luting Cements*		
Resin Luting Cement (Code, Shade)	**Main Components (Filler Content)**	**Manufacturer (Lot No.)**
G-CEM LinkForce (GL, A2)	Dimethacrylate, silica filler, initiators, stabilizers, pigments (63.0 wt%, 38.0 vol%)	GC, Tokyo, Japan (1407281)
Multilink Automix (MA, yellow)	Dimethacrylate, HEMA, barium glass filler, silica filler, ytterbium trifluoride, initiators, stabilizers, pigments (68.5 wt%, 42.5 vol%)	Ivoclar Vivadent, Schaan, Lichtenstein (150317)
NX3 Nexus (NX, yellow)	Methacrylate ester monomer, mineral fillers, initiators, stabilizers, pigments, radiopaque agent (66.5 wt%, 43.3 vol%)	Kerr, Orange, CA, USA (13394)
Panavia V5 (PV, Universal)	Bis-GMA, TEGDMA, hydrophobic aromatic dimethacrylate, hydrophilic aliphatic dimethacrylate, barium glass filler, fluoroaluminosilicate glass, silica filler, initiators, stabilizers, pigments (61.0 wt%, 38.0 vol%)	Kuraray Noritake Dental, Tokyo, Japan (A90026)
RelyX Ultimate (RU, A1)	Methacrylate monomer, alkaline filler, initiator components, stabilizers, pigments, rheological additives, fluorescence dye (67.0 wt%, 43.0 vol%)	3M ESPE, St Paul, MN, USA (588835)

Specimen Preparation for Simulated Generalized Wear

The fixture size for the generalized wear simulations was the same as the custom stainless steel fixture for simulated gap wear, with the exception of the cavity. The custom stainless steel fixtures were machined for simulated generalized wear testing with a cylindrical cavity (4.5 mm in diameter and 4.0 mm deep). Twenty specimens from each of the five resin luting cements were made for both dual-cure and chemical-cure groups.

Wear Simulation

A Leinfelder-Suzuki (Alabama) device was used for wear simulation (Figure 1). The simulator has a plastic water bath, and the custom-wear fixtures were mounted inside the four-station bath. A brass cylinder was then placed around each fixture in the bath to serve as a reservoir for the abrasive medium (ie, a water slurry of unplasticized polymethyl methacrylate [PMMA] with an average particle size of 44 μm). The medium was placed inside the brass cylinders to cover the surface of the resin luting cement in the custom fixtures. The PMMA water slurry inside the brass cylinders was approximately 6.0 mm thick over the surface of the resin cement.

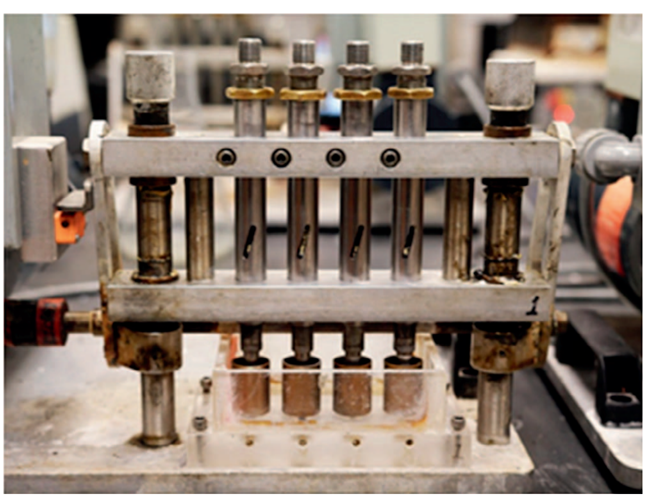

Figure 1. *Leinfelder-Suzuki (Alabama) wear simulator device.*

A stainless steel cylinder (6.5 mm in diameter) with a flat-end stylus tip was used as the antagonist for both the gap wear and generalized wear simulations. The antagonist tips were mounted on spring-loaded pistons to deliver the wear challenges. During load applications, the antagonists rotated approximately 30° as the maximum force was reached (ie, maximum load of 78.5 N at a rate of 2 Hz) and then counterrotated back to the original starting position as the load was relaxed to complete the cycle. Each set of specimens was exposed to 400,000 cycles during the gap and generalized wear simulations.

Wear Measurements

Prior to the wear simulation, each resin luting cement specimen was profiled using a Proscan 2100 noncontact optical profilometer (Scantron Industrial Products, Taunton, England) with the Proscan software. These profiles provided the pretest digitized surface contours.

After wear simulation, the specimens were ultrasonically cleaned (L&R T-14B solid state ultrasonic cleaner, L&R Manufacturing Company, South Orange, NJ, USA) in distilled water for three

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minutes and then profiled again with the Proscan 2100 unit. The x-, y-, and z-coordinates of the "before" and "after" scans were exported from the Proscan software to another computer for analysis using AnSur 3D software (Minnesota Dental Research Center for Biomaterials and Biomechanics, University of Minnesota, Minneapolis, MN, USA).

The facet depth and volume loss of the specimens were determined from the differences between the before and after data sets. A computerized fit of the data sets was first completed with the AnSur 3D software. The volume losses (VLs, mm^3) and mean depths (MDs, μm) of the wear facets were subsequently determined for both simulated gap wear and generalized wear for each of the five resin luting cements polymerized in the dual-cure and chemical-cure modes.

Scanning Electron Microscopy Observations of Resin Luting Cement Surfaces

Ultrastructural observations were conducted on the polished surfaces of the resin luting cements after argon ion etching. Three specimens per test group were observed using field-emission scanning electron microscopy (SEM; ERA 8800FE, Elionix, Tokyo, Japan).

The surfaces of the resin luting cements were polished flat to 4000 grit using a sequence of silicon carbide papers and a grinder-polisher. The surfaces were subsequently polished using abrasive discs (Fuji Star Type DDC, Sankyo-Rikagaku, Saitama, Japan) followed by a series of diamond pastes down to a particle size of 0.25 μm (DP-Paste, Struers) to bring the surfaces to a high-gloss state. The polished surface specimens intended for SEM observation were dehydrated upon immersion in aqueous tert-butanol solutions with increasing concentrations (50% for 20 minutes, 75% for 20 minutes, 95% for 20 minutes, and 100% for two hours) and were subsequently transferred to a critical-point dryer (Model ID-3, Elionix) for 30 minutes. These polished surfaces (with the objective of enhancing the visibility of the filler particles) were etched for 30 seconds with argon ion beams (EIS-200ER, Elionix) perpendicular to their surfaces at an accelerating voltage of 1.0 kV and with an ion current density of 0.4 mA/cm^2. The surfaces were then coated with a thin film of gold in a vacuum evaporator (Quick Coater SC-701, Sanyu Electron, Tokyo, Japan). The SEM observations were performed using an operating voltage of 10 kV.

Table 2: *Regression Analysis: Gap Wear and Generalized Wear Simulation Models*

Curing Method	Volume Loss (VL)		Mean Depth (MD)	
	R^2	p	R^2	p
Dual-cure group	0.994	0.000	0.913	0.011
Chemical-cure group	0.860	0.023	0.875	0.020

SEM Observations of Wear Facets After Gap Wear Simulation

The ultrastructural observations were conducted on representative wear facets of the resin luting cements from both the dual-cure and chemical-cure groups for both gap wear and generalized wear simulations using a SEM (TM3000 tabletop microscope, Hitachi-High Technologies, Tokyo, Japan). Three specimens of each resin luting cement test group were observed after gap wear and generalized wear simulations. After the wear analysis, representative specimens were coated with a thin film of gold-palladium in a vacuum evaporator (Emitech SC7620 Mini Sputter Coater, Quorum Technologies, Ashford, UK). The SEM observations were performed using an operating voltage of 15 kV.

Statistical Analyses

The VLs and MDs for gap and generalized wear of the resin luting cements were analyzed using a commercial statistical software package (SPSS Statistics Base, IBM Corp, Armonk, NY, USA). A linear regression analysis between gap wear and generalized wear on the VLs and MDs was conducted. After confirming that the distribution was normal using the Kolmogorov-Smirnov test, a two-way analysis of variance (ANOVA) and Tukey post hoc test were used to analyze each data set, with a significance level of $\alpha = 0.05$.

RESULTS

Regression Analysis

The results of the regression analysis performed on the VLs and MDs following simulated gap wear and generalized wear are shown in Table 2. For the dual-cure groups, a strong positive relationship was evident between the gap wear and generalized wear simulation models for both the VL (R^2=0.994) and MD (R^2=0.913). In addition, a strong relationship was also observed between the gap wear and the generalized wear simulation models for both the VL (R^2=0.860) and MD (R^2=0.875) of the chemical-cure groups. All of these correlations were statistically significant at a level of $\alpha = 0.05$.

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Table 3: *Simulated Gap Wear of Resin Luting Cements*[a]

Volume Loss (VL)

Resin Luting Cement	Volume Loss (mm^3)		
	Dual-Cure Group	Chemical-Cure Group	% Difference
GL	0.023 (0.007) a,A	0.028 (0.006) a,A	21.7
MA	0.026 (0.010) a,A	0.039 (0.008) b,B	50.0
NX	0.028 (0.007) a,A	0.042 (0.009) b,B	50.0
PV	0.029 (0.014) a,A	0.033 (0.008) a,b,A	13.8
RU	0.030 (0.007) a,A	0.044 (0.006) b,B	46.7

Abbreviations: GL, G-CEM LinkForce; MA, Multilink Automix; NX, NX3 Nexus; PV, Panavia V5; RU, RelyX Ultimate.
[a] *Same lowercase letter in same vertical column indicates no significant difference* ($p>0.05$). *Same capital letter within individual rows indicates no significant difference* ($p>0.05$).

Gap Wear Simulation

The VL and MD results for the wear facets of the resin luting cements after the gap wear simulations are shown in Tables 3 and 4, respectively. The two-way ANOVA results indicated that the material type ($p<0.001$), curing method ($p<0.001$), and interaction between the material type and curing method ($p<0.001$) significantly affected the VLs and MDs of the five resin luting cements. Significant differences were evident among the materials for both the dual-cure and chemical-cure groups. The trend in the VLs and MDs of the dual-cure (GL-MA-NX-PV-RU) and chemical-cure (GL-PV-MA-NX-RU) groups following the gap wear simulations were similar. Unlike MA, NX, and RU, the VL and MD of the wear facets of GL and PV were not influenced by the curing method.

Generalized Wear Simulation

The VL and MD results for the resin luting cements after generalized wear simulation are shown in Tables 5 and 6, respectively. The two-way ANOVA results revealed a significant effect for the material type ($p<0.001$), curing method ($p<0.001$), and interaction between the material type and curing method ($p<0.001$) for the VLs and MDs of the five resin luting cements. Significant differences were evident among the materials for both the dual- and chemical-cure groups. The trends in wear for the VLs and MDs of the dual- (GL-MA-NX-PV-RU) and chemical- (GL-PV-MA-NX-RU) cure groups, following generalized wear simulation are similar. Unlike MA, NX, and RU, the VLs and MDs of the wear facets of GL and PV were not influenced by the curing method.

Table 4: *Simulated Gap Wear of Resin Luting Cements*

Mean Depth (MD)

Resin Luting Cement	Mean Depth (μm)		
	Dual-Cure Group	Chemical-Cure Group	% Difference
GL	35.4 (9.2) a,A	44.4 (11.7) a,A	25.4
MA	38.2 (13.0) a,b,A	62.7 (11.9) c,B	64.1
NX	40.4 (8.3) a,b,A	64.3 (9.7) b,B	59.2
PV	42.9 (7.2) a,b,A	52.3 (9.9) a,c,A	21.9
RU	45.2 (9.6) b,A	69.5 (10.4) b,B	53.8

Abbreviations: GL, G-CEM LinkForce; MA, Multilink Automix; NX, NX3 Nexus; PV, Panavia V5; RU, RelyX Ultimate.
[a] *Values in parentheses are standard deviations. Same small case letter in same vertical column indicates no significant difference* ($p>0.05$). *Same capital case letter within individual rows indicates no significant difference* ($p>0.05$).

Table 5: *Simulated Generalized Wear of Resin Luting Cements*[a]

Volume Loss (VL)

Resin Luting Cement	Volume Loss (mm^3)		
	Dual-Cure Group	Chemical-Cure Group	% Difference
GL	0.426 (0.090) a,A	0.498 (0.096) a,A	16.9
MA	0.525 (0.088) a,A	0.721 (0.102) b,B	37.3
NX	0.579 (0.140) b,A	0.764 (0.142) c,B	31.9
PV	0.619 (0.092) b,A	0.673 (0.120) b,A	8.7
RU	0.664 (0.122) b,A	0.960 (0.106) d,B	44.6

Abbreviations: GL, G-CEM LinkForce; MA, Multilink Automix; NX, NX3 Nexus; PV, Panavia V5; RU, RelyX Ultimate.
[a] *Values in parentheses are standard deviations. Same small case letter in same vertical column indicates no significant difference* ($p>0.05$). *Same capital case letter within individual rows indicates no significant difference* ($p>0.05$).

SEM Observations of Resin Luting Cement Surfaces

Representative SEM images of the polished resin luting cement surfaces are shown in Figure 2. The

Table 6: *Simulated Generalized Wear of Resin Luting Cements*[a]

Mean Depth (MD)

Resin Luting Cement	Mean Depth (μm)		
	Dual-Cure Group	Chemical-Cure Group	% Difference
GL	35.3 (6.9) a,A	39.4 (8.4) a,A	11.6
MA	43.5 (6.6) b,A	56.3 (9.3) b,B	29.4
NX	50.3 (7.2) c,A	66.7 (10.6) c,B	32.6
PV	51.0 (9.9) c,A	55.8 (9.1) a,b,A	9.4
RU	54.3 (9.4) c,A	73.2 (11.5) c,B	34.8

Abbreviations: GL, G-CEM LinkForce; MA, Multilink Automix; NX, NX3 Nexus; PV, Panavia V5; RU, RelyX Ultimate.
[a] *Values in parenthesis are standard deviations. Same small case letter in same vertical column indicates no significant difference* ($p>0.05$). *Same capital case letter within individual rows indicates no significant difference* ($p>0.05$).

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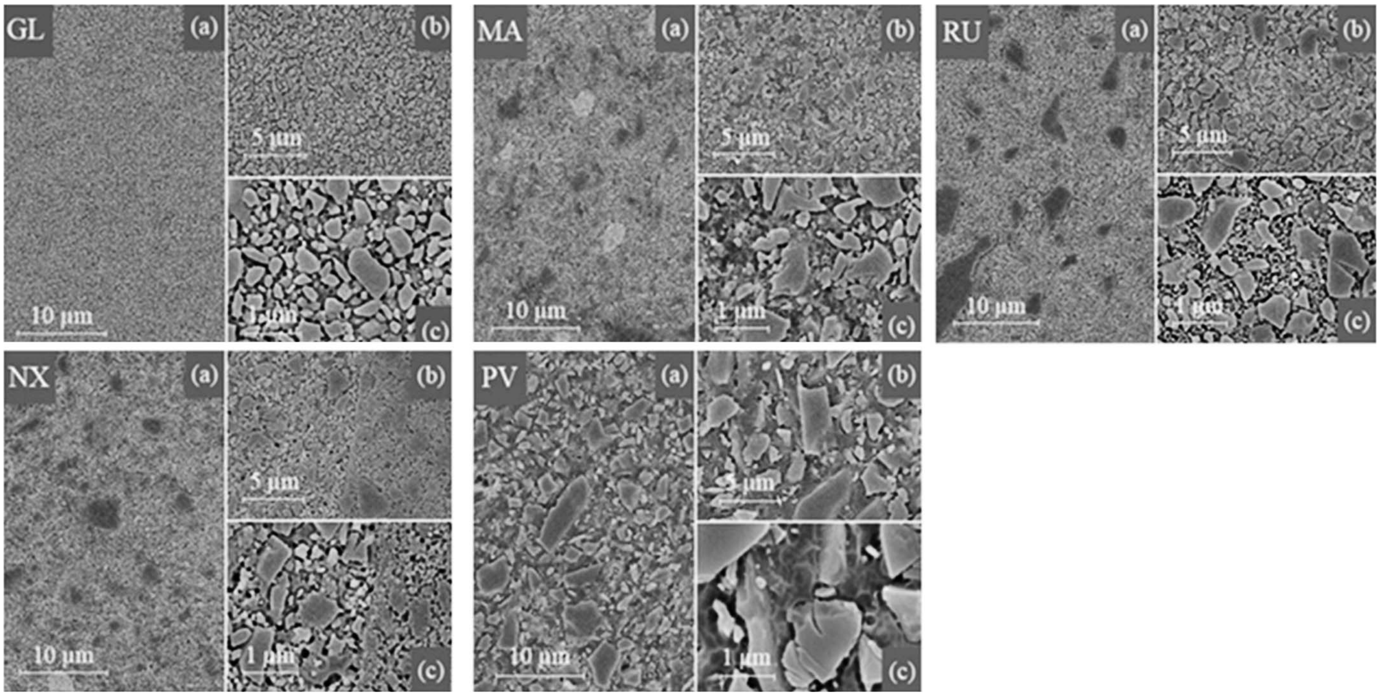

Figure 2. *Representative scanning electron microscope images of polished resin luting cement surfaces at (a): 2500× magnification, (b): 10,000× magnification, and (c): 30,000× magnification. The sizes and distributions of fillers in the different types of resin luting cements vary depending on the material: GL, wide size range (0.1-1.0 μm) of small irregular particles; MA, wide size range (1-8 μm) of irregular particles; NX, wide size range (0.1-10 μm) of irregular particles; PV, wide size range (0.1-15 μm) of irregular particles; RU, wide size range (0.1-20 μm) of irregular particles.*

argon ion etching revealed clear differences in the filler particle size, shape, and distribution of the specimens studied. The resin luting cement specimens exhibited a wide variety of filler particle sizes and shapes.

The SEM images of polished GL surfaces, with argon ion etching, showed the presence of small irregular particles with a wide size distribution (0.1-1.0 μm). The SEM images of polished MA surfaces, with argon ion etching, revealed the presence of irregular particles with wide size distributions (0.1-8 μm). For the NX, PV, and RU specimens, the SEM images also revealed the presence of irregular particles with wide size distributions (0.1-10 μm, 0.1-15 μm, and 0.1-20 μm, respectively).

SEM Observations of Wear Facets After Gap Wear Simulation

Representative SEM images of the wear facets that were obtained after conducting the gap wear simulation of the dual- and chemical-cure groups are shown in Figure 3. The SEM images of the worn surfaces of the MA, NX, and RU, within the chemical-cure group after performing the gap wear simulations, showed clearer gap formations at lower magnification as compared with those of the dual-cure group. The higher magnification micrographs appeared to indicate a greater extent of filler particle plucking for the chemical-cure group as compared with the dual-cure group. On the other hand, the SEM images obtained after the gap wear simulation of the worn surfaces of the GL and PV, which were polymerized using the two different curing methods, did not show any clear differences.

SEM Observations of Wear Facets After Generalized Wear Simulation

Representative SEM images of wear facets of the dual-cure and chemical-cure groups after generalized wear simulation are shown in Figure 4. The SEM images obtained for the worn surfaces of the MA, NX, and RU, within the chemical-cure group after the generalized wear simulations, appeared to have a greater degree of filler particle plucking compared with the dual-cure group. The SEM images obtained after the generalized wear simulation for the worn surfaces of the GL and PV, which were cured using the two different methods, did not show any clear differences.

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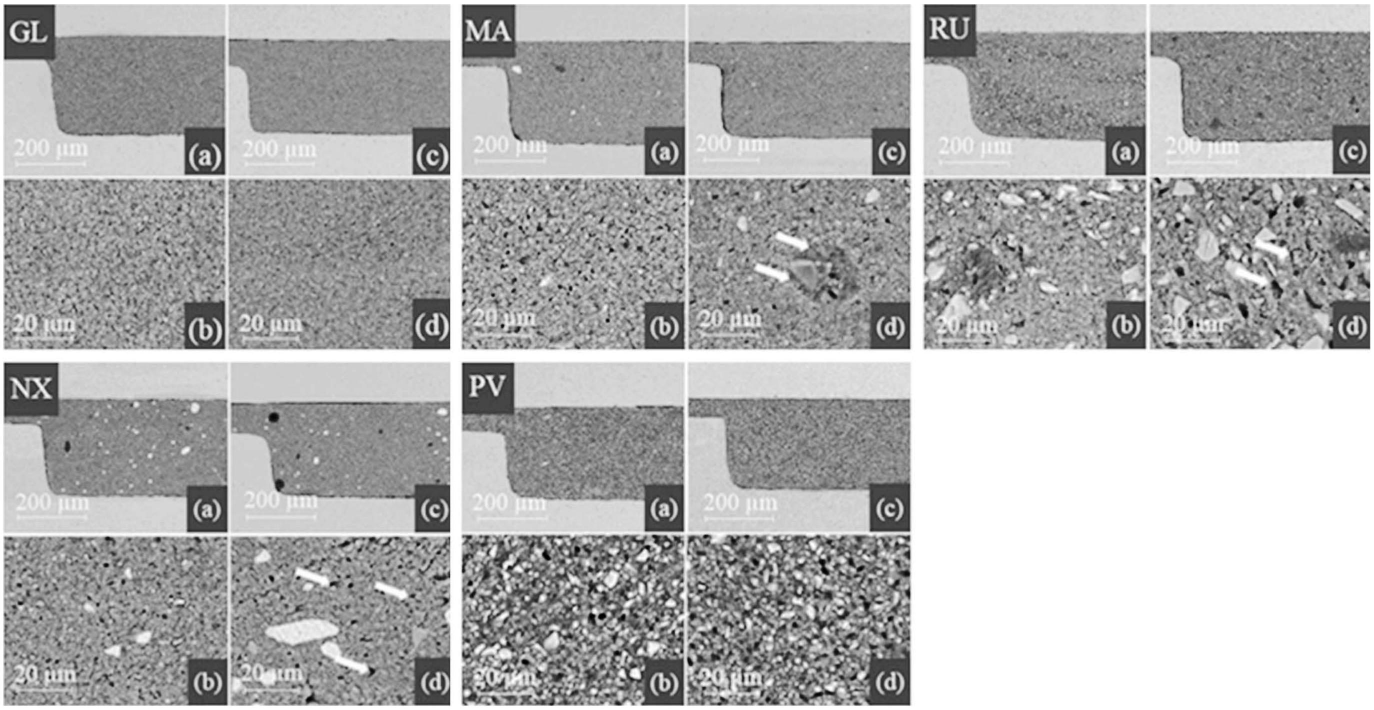

Figure 3. *Representative scanning electron microscope (SEM) images of the wear facets after the simulated gap wear of resin luting cements within the dual-cure group at (a): 250× magnification and (b): 2500× magnification and within the chemical-cure group at (c): 250× magnification and (d): 2500× magnification. The SEM images of the worn surfaces of MA, NX, and RU within the chemical-cure group show a greater degree of filler particle plucking (white arrows, higher magnifications) than the dual-cure group. On the other hand, the SEM images obtained after simulated gap wear for the worn surfaces of GL and PV samples cured using different methods do not show any clear differences.*

DISCUSSION

Two wear simulation models were used in this laboratory study to assess the relative wear resistances of five resin luting cements. The simulated wear results for the resin luting cements generated using a new gap wear model were compared with those obtained with a more commonly used generalized wear simulation model. In both models, a flat-ended stainless-steel antagonist was used to induce wear via an abrasive medium composed of a water slurry of PMMA beads. The dual-cure and chemical-cure groups for the five resin luting cements were assessed using the two wear simulation models along with SEM observations.

In a previous study,[11] simulated wear of self-adhesive resin cements was investigated using both a gap (for toothbrush abrasion) and the Academisch Centrum for Tandheelkunde Amsterdam (ACTA) wear simulation models. The investigators reported that the self-adhesive resin cements showed good wear resistance against toothbrush abrasion but not against ACTA wear. Thus, there was no correlation (R^2=0.0567) between the two wear models. However, in the present study, after comparing simulated gap wear and generalized wear of five resin luting cements, strong positive correlations were found between the two wear models for both the dual-cure (VL [R^2=0.994] and MD [R^2=0.913]) and chemical-cure (VL [R^2=0.860] and MD [R^2=0.875]) groups.

Barkmeier and others[12,13] conducted several wear simulation studies with a frequently used generalized wear simulation model to evaluate the wear resistance of resin-based materials. In addition, they also reported good agreement between simulated generalized wear and clinical wear of resin composite materials.[14] A new gap wear simulation model was used in the present study in an effort to assess the wear resistance of resin luting cements occurring at the marginal areas of cemented clinical restorations. The new gap wear simulation model delivers wear challenges with the same stainless steel antagonist tip used in the generalized wear simulation model. The primary difference is the area of resin luting cement being exposed to the wear process. Overall, the correlation between the wear characteristics (in terms of VL and MD) of the resin luting cements in the two wear simulation models was excellent. Although the objective of using the new gap wear simulation model was to more closely replicate the type of cement abrasion that may occur

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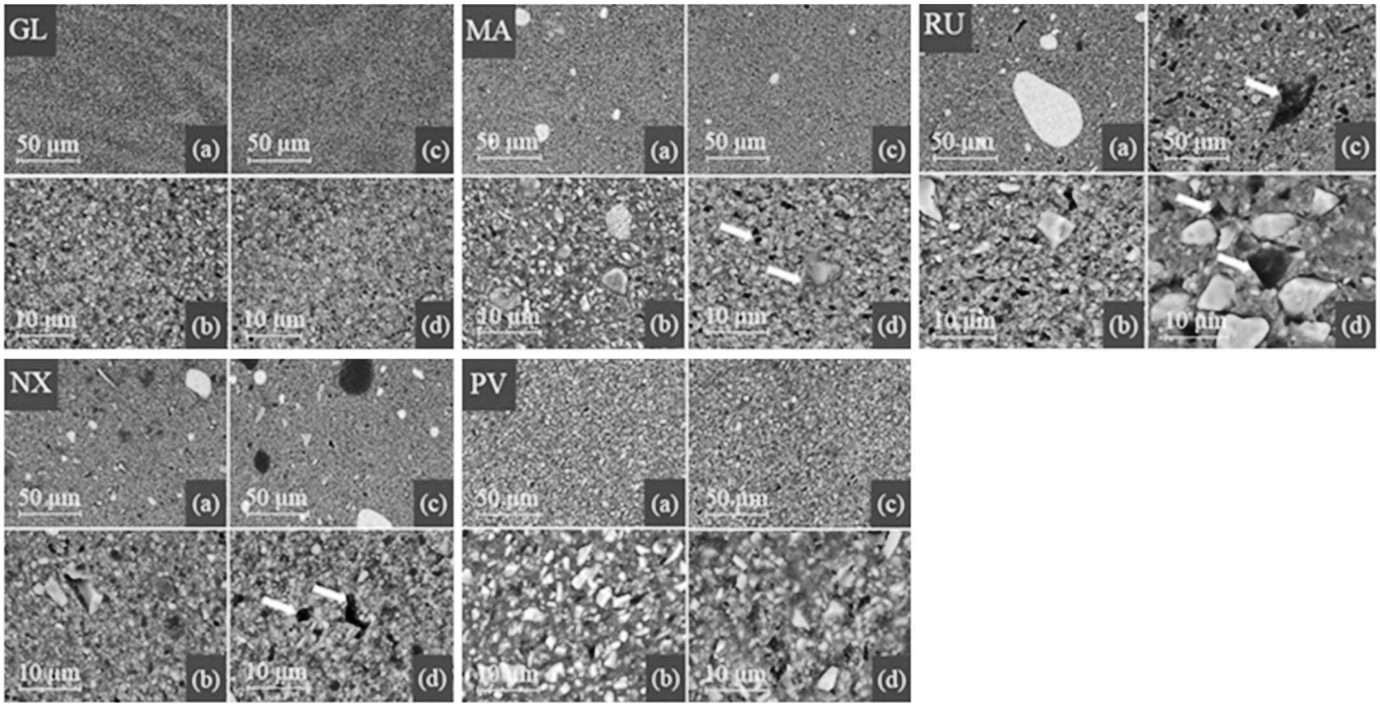

Figure 4. *Representative SEM images of the wear facets after simulated generalized wear of resin luting cements within the dual-cure group at (a): 1000× magnification and (b): 5000× magnification and within the chemical-cure group at (c): 1000× magnification and (d): 5000× magnification. The SEM images of the worn surfaces of MA, NX, and RU within the chemical-cure group after the generalized wear simulations seemed to have higher extents of filler particle plucking (white arrows) than the dual-cure group. The SEM images obtained after generalized wear for the worn surfaces of GL and PV samples cured using different methods do not show any clear differences.*

in the oral cavity, the results indicated that the wear resistance of resin luting cements can be assessed with the standard generalized wear simulation model. However, the new gap wear simulation model does appear to mimic the type of wear challenges encountered at marginal areas of cemented restorations in the oral cavity. The results of the new gap wear simulation model reaffirmed that thin film abrasive wear of resin luting cement in marginal closure areas remains an issue for the long-term clinical success of cemented restorations.

Simulated gap wear and generalized wear of resin luting cements of the dual-cure and chemical-cure groups clearly showed significant differences among the different materials. However, the observed trends (dual-cure group: GL-MA-NX-PV-RU; chemical-cure group: GL-PV-MA-NX-RU) in the simulated wear characteristics of VL and MD for the five resin luting cements were the same in the two wear simulation models, regardless of the curing method (Tables 3-6).

It has been reported that the filler load plays a particularly important role in the wear resistance of resin-based materials, with higher filler loads reducing the level of wear.[15] The filler load values provided by the manufacturers varied greatly among the resin luting cements (Table 1), although a clear relationship between the simulated wear and the filler load was not evident in the present study.

Conversely, a clear relationship between the simulated wear and the filler size was found. The filler particle size trend among the polished resin luting cements (GL-MA-NX-PV-RU), as determined from the SEM observations using argon ion etching, was the same as the trend for both simulated gap wear and generalized wear models within the dual-cure group. It has been reported that the filler particle size affects the simulated wear of resin composites.[16] That is, resin composites with fillers having low particle sizes showed lower simulated wear. These results for resin cements are consistent with the earlier results for restorative resin composites.[17] GL from the dual-cure group showed smaller filler particles and thus lower simulated wear. On the other hand, RU, which had larger filler particles and a broad size distribution, exhibited greater wear regardless of the wear simulation model. Therefore, both the simulated gap and generalized wear of the resin luting cements were influenced by the filler particle size, as in the case of resin composites. The

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differences between the wear resistances of different types of resin luting cements have been hypothesized to result from the lower interparticle spacing between small filler particles. Because small filler particles are more closely packed, the resin matrix between them is protected from further wear.[18] On the other hand, when larger filler particles are removed from the resin composite surface, a void is produced, thereby exposing the underlying resin matrix to wear.[19] Also, the removed particles can cause further abrasion of the surfaces of resin-based materials, resulting in increased wear.[19]

In addition, although different types of resin luting cements having similar shades should ideally be used for a comparative study, the types of resin luting cement used herein showed slight differences in shade (Table 1) due to the limited availability of shades from the manufacturers. It has been reported that the shades and translucencies of resin-based materials significantly influence their degrees of conversion.[20] Therefore, the differences between the shades and translucencies of the types of resin luting cements used herein may have contributed to the material differences in observed wear in simulated gap wear and generalized wear.

The simulated gap and generalized wear of the resin luting cements differed significantly depending on the curing method. The trend observed for the simulated gap wear and generalized wear of the chemical-cure group (GL-PV-MA-NX-RU) was different than that of the dual-cure group (GL-MA-NX-PV-RU) (Tables 3-6). Previous studies comparing the influence of the curing method on the degree of conversion of resin luting cements have generally found that photo-curing produces a significantly higher degree of conversion than does chemical curing alone for dual-cure resin luting cements.[21,22] In addition, the wear resistance and mechanical properties of resin-based materials were reported to increase by improving the degree of conversion.[23,24] The ability of dual-cure resin luting cement to cure effectively in the chemical-curing mode is key to the long-term clinical success of cemented restorations, particularly when photo-curing is not possible or is limited. Therefore, based on the results of this study, clinicians should pay more attention to the different setting characteristics of dual-cure resin luting cement when selecting these materials for clinical use.

The VLs and MDs in the gap wear facets of MA, NX, and RU significantly increased (VL: 46.7%-50.0%; MD: 53.8%-64.1%) for the chemical-cure group as compared with the dual-cure group. Similarly, the VLs and MDs in the generalized wear facets of MA, NX, and RU significantly increased (VL: 31.6%-44.6%; MD: 29.4%-34.8%) for the chemical-cure group samples as compared with the dual-cure group. On the other hand, the VLs and MDs of GL and PV showed similar values ($p>0.05$) for both gap wear and generalized wear simulation models and both the dual- and chemical-cured groups.

The SEM images of the worn surfaces (gap wear and generalized wear simulations) of the MA, NX, and RU, within the chemical-cure group, appeared to show a greater degree of cracking and filler particle plucking than the dual-cure group. On the other hand, the GL and PV wear simulation specimens cured using the different polymerization methods did not show any clear differences. These findings might be explained by the different compositions of the materials. Polymerization of dual-cure resin luting cement can be activated either by inducing a photo initiator (eg, camphorquinone) or breaking the molecules of a chemical initiator (eg, benzoyl peroxide) such that free radicals are formed to initiate polymerization reactions.[25,26] The contents of the initiators of photo- and chemical-polymerization in resin luting cement differ depending on the material.[27] For instance, the benzoyl peroxide content of some types of resin luting cements are double those of other materials. Some cements are overly dependent on photo polymerization, which may lead to inadequate polymerization and performance in clinical situations.[28] Unfortunately, detailed information from the manufacturers about the contents of photo- and chemical-initiators in resin luting cement is very limited; thus, further comparisons are difficult.

On the basis of the results of this study, the first null hypothesis that there would be no relationship between the simulated gap wear and the generalized wear of different types of resin luting cement was not rejected. On the other hand, the second null hypothesis that the simulated gap wear and generalized wear of different types of resin luting cement are not influenced by the type of material or curing method was rejected.

CONCLUSION

The results of this study indicate that the simulated wear of resin luting cements generated using a new gap model is very similar to that produced by a commonly used generalized wear simulation model. Thus, both models can be used to assess the wear resistance of resin luting cements. In addition, dual

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curing appears to result in greater wear resistance of resin luting cement compared with chemical curing in most cases, but some types of resin luting cements showed no significant differences between the two curing methods. Therefore, the influence of the curing method on resin luting cements seems to be material-dependent.

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Conflict of Interest

The authors of this manuscript 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.

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