In Vitro Wear Resistance of Self-Adhesive Restorative Materials

Mark A. Latta[a] / Akimasa Tsujimoto[b] / Toshiki Takamizawa[b] / Wayne W. Barkmeier[c]

Purpose: To investigate simulated localized and generalized wear of self-adhesive restorative materials.

Materials and Methods: Three commercially available restorative materials and one experimental material with self-adhesive properties were evaluated. The experimental material was tested in both light-cured and self-cured conditions. Activa (A), Fuji II LC (F), and Equia Forte (E) and the experimental material ASAR-MP4 (S) were investigated. Two kinds of wear were simulated in an Alabama wear machine. Localized wear was simulated with a stainless-steel ball bearing antagonist and generalized with a flat-ended stainless-steel cylinder antagonist. The wear challenge was carried out in an aqueous slurry of polymethyl methacrylate beads. Material volume loss was measured on polyvinyl siloxane replicates of each worn surface using a Proscan 2100 noncontact profilometer in conjunction with Proscan and AnSur 3D software.

Results: There were significant differences ($p < 0.05$) among the materials for both generalized and localized wear. The experimental material in both curing modes exhibited significantly less localized wear than F and A and significantly less generalized wear than F and E.

Conclusion: Self-adhesive materials offer unique handling properties for direct placement of posterior restorations in permanent teeth. The experimental material ASAR-MP4 generated similar wear values to the other self-adhesive materials tested.

Keywords: localized wear, generalized wear, self-adhesive, bulk fill, glass ionomer

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Glass-ionomer (GIC) and resin-modified glass-ionomer cements (RMGIC) have unique properties such as fluoride ion release and recharging abilities, inhibiting bacterial acid metabolism, and preventing enamel decalcification.[20,29,31] Other clinical beneficial properties of these materials include a thermal expansion coefficient similar to that of dentin, biocompatibility, the ability to bulkfill a cavity, and adhesion to tooth structure without pretreatment.[7,9,40] These materials have a wide range of applications in dentistry and are also routinely used in pediatric dentistry and in class V cervical erosion lesions.[5,14,27,40] However, for use in permanent posterior restorative indications, these materials express lower physical properties[12,34] than what is desired for these high stress indications. Bulk fracture and marginal chipping of restorations have been cited as major problems regarding the failure of these materials.[34] The fracture toughness and flexural strength of these materials have become important factors in their longevity[17,18] because over time, wear, fatigue, and internal stress-strain from thermal contraction and expansion may create plastic deformation and marginal leakage.[36,37] Nevertheless, even with these limitations, the ease of use in clinical situations where controlling moisture for an extended period of time makes these materials desirable.[14] The demand for these forgiving materials to be used in high-stress clinical indications has led to new developments aimed at improving their strength while maintaining their favorable biological and handling properties. Some of the strategies for property improvement focus on optimization of the dispersion and particle size of both reactive and reinforcing fillers as well as changes in the polyacrylic acid monomer and other oligomers in the continuous phase of the set material.[32]

[a] *Professor and Dean, Department of General Dentistry, Creighton University School of Dentistry, Omaha, NE, USA. Hypothesis, monitored specimen preparation and experiments, wrote the manuscript, discussed the results, commented on the manuscript at all stages.*

[b] *Assistant Professor, Department of Operative Dentistry, Nihon University School of Dentistry, Tokyo, Japan. Consulted on statistical evaluation, discussed the results, commented on the manuscript at all stages.*

[c] *Special Professor and Dean Emeritus, Department of General Dentistry, Creighton University School of Dentistry, Omaha, NE, USA. Contributed to experimental design, proofread the manuscript, discussed the results, commented on the manuscript at all stages.*

Correspondence: *Dr. Mark Latta, Creighton University School of Dentistry, 2500 California Plaza, Omaha, NE 68178 USA. Tel: +1-402-280-5062; e-mail: mlatta@creighton.edu*

Table 1 Self-adhesive restorative materials

Restorative	Manufacturer	Main components	Code
ASAR-MP4 Lot No. 1711004202	Dentsply Sirona; Konstanz, Germany	Aluminum-phosphor-strontium-sodium-fluoro-silicate glass, water, highly dispersed silicon dioxide, acrylic acid, polycarboxylic acid, ytterbium fluoride, bifunctional acrylate, self cure initiator, iron oxide pigments, barium sulfate pigment, manganese pigment, camphorquinone (photoinitiator), stabilizer	S
Fuji II LC Lot No. 1707132	GC; Tokyo, Japan	Fluoro-alumino-silicate glass, water, polyacrylic acid, HEMA, urethane dimethacrylate	F
Equia Forte Lot No. 170807A	GC	Fluoro-alumino-silicate glass, water, polyacrylic acid, polybasic carboxylic acid, camphorquinone (photoinitiator)	E
Activa Lot No. 171102	Pulpdent; Watertown, MA, USA	Bioactive glass, silica, diurethane modified with hydrogenated polybutadiene, methacrylate monomers, modified polyacrylic acid, sodiumfluoride, camphorquinone (photoinitiator)	A

One clinical aspect of longevity for posterior restorations is the ability to resist masticatory forces and the resultant wear on the restorative material. Two distinct kinds of wear have been described based on laboratory and clinical observations.[19] One of these is wear initiated by generalized conditions (the type of wear generated by a food bolus during mastication) and the other is wear generated under localized conditions (represented by direct tooth-to-restorative material contact). Some authors[22,26] have suggested that localized wear may be a more important contributor to the breakdown of a material, and contact wear may be more than two times as great as that in non-contact areas. Clinical studies offer the most meaningful data on the performance of any given material. However, the time involvement and costs associated with clinical studies have driven researchers seeking to predict clinical performance to employ wear simulation of prototype materials as a screening tool and predictor of clinical performance. One such in vitro simulation model involved a laboratory simulator, sometimes referred to as the Alabama wear testing machine,[23] capable of evaluating both generalized and localized wear. This system transfers masticatory stresses to a composite specimen by means of a flattened steel (generalized wear) or a stainless steel conical stylus (localized wear) in the presence of a slurry of polymethylmethacrylate beads (PMMA). This device has facilitated the development of in vitro studies capable of helping predict in vivo performance. Enhancements of the original mechanical model have been made to improve reliability and repeatability of in vitro wear testing.[1,3,16,33] Using these enhanced protocols, studies have shown a correlation between in vitro wear and in vivo generalized wear of dental restorative materials.[1,2]

A limited number of investigations have evaluated the wear resistance characteristics of self-adhesive, bulk-fill restorative materials. The purpose of this laboratory study was to investigate the generalized and localized wear of four self-adhesive restorative materials. The null hypotheses tested were 1) there are no differences in localized wear among the materials tested and 2) there are no differences in generalized wear among the materials tested.

MATERIALS AND METHODS

Study Materials

The self-adhesive materials used in this study are shown in Table 1. These materials included three commercially available materials and one experimental material. They were: 1. Fuji II LC (F) (GC; Tokyo, Japan), 2. Equia Forte (E) (GC), 3. Activa (A) (Pulpdent; Watertown, MA, USA), and 4. ASAR-MP4 (S) (Dentsply Sirona; Konstanz, Germany).

Specimen Preparation

Twelve specimens of each material were prepared for simulated localized wear (OCA wear) and twelve specimens of each material were prepared for generalized wear (CFA wear). For ASAR-MP4, 24 specimens were prepared for each wear challenge, with 12 visible light cured and 12 self-cured only. Cylinder-shaped custom stainless steel fixtures used for the localized wear were machined with a cylindrical cavity 5 mm in diameter and 3 mm in depth. Stainless steel fixtures for generalized wear testing were machined with a cylindrical cavity 4.5 mm in diameter and 4 mm in depth. Materials in a mixing capsule were mixed for 10 s in a Pro-Mix 2 mixing device and placed directly onto the wear specimen fixtures.

The experimental material ASAR-MP4 (S/LC), Fuji II LC and Activa were allowed to self-cure at room temperature for 1 min prior to visible light curing for 30 s using a SmartLite Focus LED curing unit. For Equia Forte and a second group of specimens for the experimental material (S/SC), no light curing was used; the sample specimens were allowed to self-cure for 6 min at room temperature. All specimen preparation was done in a laboratory equipped with lighting designed to prevent polymerization from ambient light. Following the curing protocols, the specimens were stored for 24 h in distilled

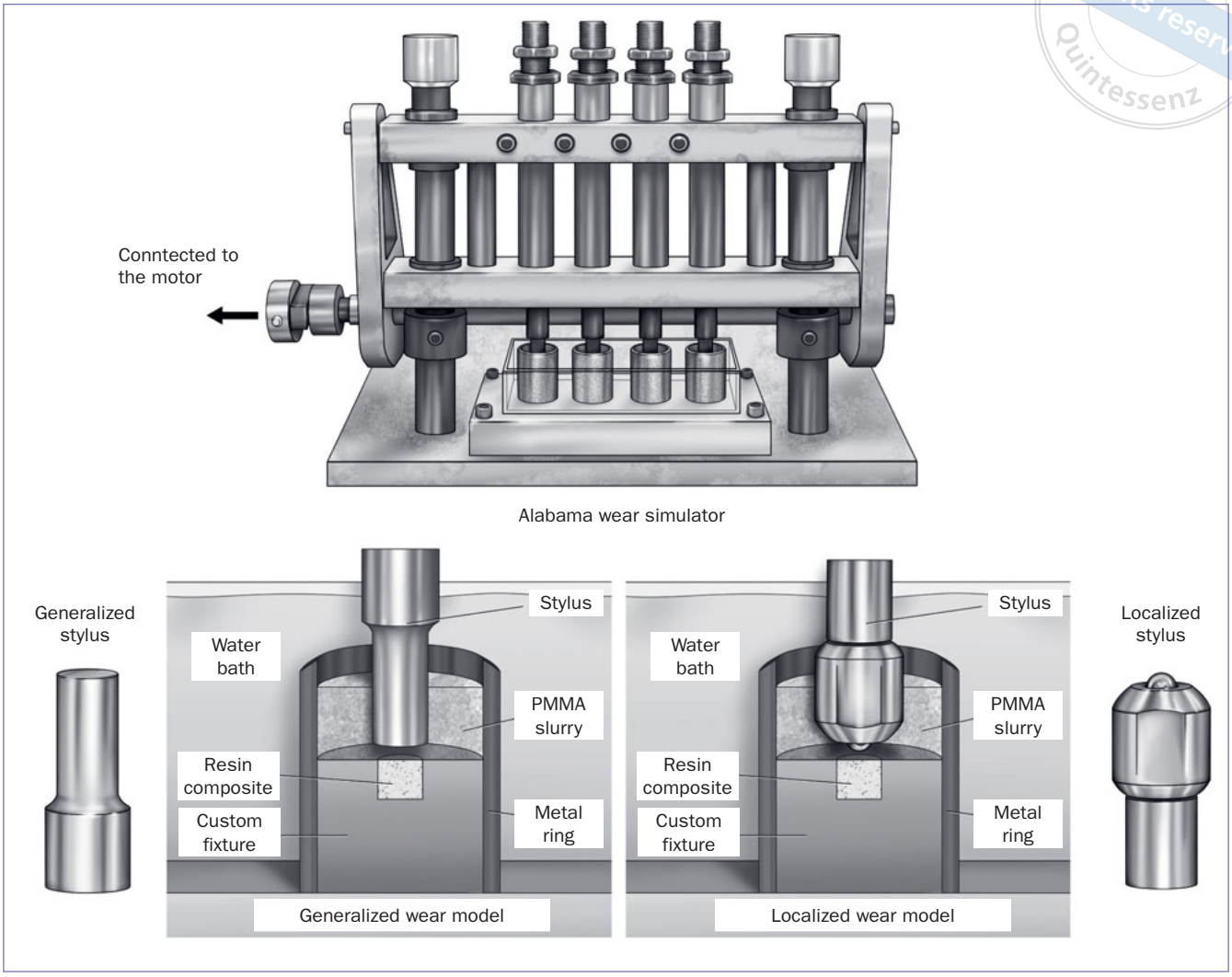

Fig 1 Schematic illustration of the experimental setup for generalized and localized wear based on the Alabama wear testing machine.

water at 37°C. After 24 h, the restorative surfaces were polished flat (Fig 1) to 4000 grit using a sequence of silicon carbide papers (Struers; Ballerup, Denmark).

Wear Testing

An Alabama wear test machine was used for this study. The simulator has a plastic water bath, and the custom wear fixtures were mounted inside the four-station bath. A brass cylinder was placed around each fixture in the bath to serve as a reservoir for an abrasive medium. This medium consists of a water slurry (60% by weight) of unplasticized polymethyl methacrylate powder (HG-5 Polymer 68168, Dentsply Sirona) with an average particle size of 44 µm. The medium was placed inside the brass cylinders to cover the surface of the restorative material in the custom fixtures. The water slurry of PMMA inside the brass cylinders was approximately 6.0 mm deep over the surface of the test materials.

Two different wear antagonists were used in this study. For the localized (OCA) wear simulation, a stainless-steel ball bearing (2.387 mm radius) was mounted inside a collet assembly. The antagonist for the generalized (CFA) wear simulation was a stainless-steel cylinder (6.5 mm in diameter) with a flat-end stylus tip. During specimen polishing, there is differential abrasion of the restorative material compared to the perimeter made of stainless steel. Thus, the flattened area of the test material is slightly below the stainless steel area surrounding the 4.5-mm diameter of the material specimen. At the beginning of the wear test and at the lowest point of contact with the stainless steel fixture, the gap between the antagonist and specimen is estimated to be 5 µm. As wear progresses, this gap will increase. At no point in the generalized wear challenge does the antagonist come into direct contact with the material specimen. For each of the wear cycles, the antagonist for both localized and gener-

Table 2 Volume loss for localized wear

Material	Localized wear (volume mm^3)
ASAR-MP4 LC	0.153 ± 0.031[a]
ASAR-MP4 SC	0.166 ± 0.044[b]
Equia Forte (E)	0.167 ± 0.044[b]
Fuji II LC (F)	0.330 ± 0.077[c]
Activa (A)	0.338 ± 0.056[c]

Groups marked with the same small letter were statistically similar ($p > 0.05$). LC = light cured; SC = self-cured.

Table 3 Volume loss for generalized wear

Material	Generalized wear (volume mm^3)
ASAR-MP4 LC	0.249 ± 0.077[a]
ASAR-MP4 SC	0.266 ± 0.072[a]
Activa (A	0.268 ± 0.059[a,b]
Equia Forte (E)	0.299± 0.077[b]
Fuji II LC (F)	0.564 ± 0.096[c]

Groups marked with the same superscript letter were statistically similar ($p > 0.05$). LC = light cured; SC = self-cured.

alized wear rises above the specimen by 2 mm, descends to the surface, and upon contact with the specimen (localized) or the fixture (generalized) the antagonist rotates clockwise 30 degrees. The antagonist tips were mounted on spring-loaded pistons to deliver the wear challenges. During the application of the load, the antagonists rotated approximately 30 degrees as the maximum force was reached (maximum load of 78.5 N at a rate of 2 Hz), and then counterrotated to the original starting position as the load was relaxed to complete the cycle. Each set of specimens was exposed to 400,000 cycles in the wear simulator. The experimental apparatus and configuration of both localized and generalized wear specimens are shown in Fig 1.

Wear Measurements

Prior to wear simulation, each restorative material surface was replicated with a polyvinyl impression material (Aquasil Ultra LV, Dentsply Sirona). This was done to prevent the formation of desiccation artifacts on the test specimen surfaces during surface profiling. Each surface impression was profiled using a Proscan 2100 noncontact optical profilometer (Scantron Industrial Products; Taunton, UK) with Proscan software. The impression material used is capable of producing a highly accurate replicate of the surface with special resolution of surface detail at the 1-µm level.[13] These profiles provided the pre-test digitized contours (12 specimens for each of the six test groups for both localized and generalized wear testing).

After the 400,000 wear cycles, the specimens were ultrasonically cleaned (L&R T-14B solid-state ultrasonic cleaner, L&R Manufacturing; South Orange, NJ, USA) in distilled water for three minutes and then re-impressed. The surface replicates were profiled again using 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 use of pre- and post-wear profiling takes into account any variations from the assumed flat surface finish and assures that any differences pre- and post-test are derived from the wear challenge.

Volume loss measurements were determined from differences between the before and after data sets. A computerized fit was completed using the before and after data sets in AnSur 3D, and volume loss (VL, mm^3) was then determined for both localized and generalized wear simulation for each of the six resin composites.

Statistical Analysis

One-way ANOVA followed by Tukey's significant difference (HSD) test ($\alpha = 0.05$) was used for analysis of the localized and generalized volume loss data.

RESULTS

Localized Wear

The results for the localized wear volume loss of the materials tested are shown in Table 2. S/LC exhibited the lowest wear compared to the other materials tested ($p < 0.05$). The self-cured specimens S/SC and E exhibited similar volumetric loss, which was significantly less than that of F and A.

Generalized Wear

The results for the generalized wear volume loss of the materials tested are shown in Table 3. Generalized volume loss was similar for S/LC, S/SC, and A ($p > 0.05$). E and F exhibited the highest generalized wear volume loss.

DISCUSSION

For load bearing (occlusal posterior or occlusal-proximal) restorations, self-adhesive restorative materials are of great interest compared to bonded resin composites, due to their relative moisture insensitivity and favorable handling characteristics.[25] While the most common recommendation for the replacement of lost tooth structure is to use a microhybrid or nanohybrid resin composite, recent innovations in

the creation of high-viscosity glass ionomers (HVGIC), bioactive glass ionomers and composite hybrid materials have sought to combine the durability and wear resistance of resin composites with the favorable characteristics of glass-ionomer cements.[21,30,35] Recent evidence from clinical trials of a HVGIC in permanent posterior teeth showed acceptable clinical performance, suggesting a promising future for extending the indications of these materials.[14,28] The wear model employed in this study is capable of simulating some of the kinds of wear found on occlusal surfaces. The generalized model is designed to simulate wear from the erosive behavior of the solid particles in a food bolus. This form of wear is generated when food particles are pressed and sheared across the surface and occurs clinically in the contact-free areas (CFA). The Alabama localized model, while using a "food bolus" slurry, generates much higher point stresses on the surface, analogous to occlusal contacts on the restorative material surface.

While some early investigations suggested the restorative material's surface hardness as a key factor in wear resistance,[15] more recent thinking suggests the degree of wear is affected more significantly by surface structure and surface roughness.[10] No consistent correlation was observed in a study of glass-ionomer and resin glass-ionomer materials, in which compressive strength, flexural strength, Knoop hardness, and diametral tensile strength and wear were evaluated.[39] These authors concluded that structural parameters such as the polymer matrix, glass fillers and the bonding between the continuous and discontinuous phases of the material had greater impacts on wear behavior.

While the generalized and localized models reflect very different kinds of wear, typically the rank ordering of resin-based materials is similar among materials evaluated with both wear challenges. In the current experiment, however, there are some notable differences in the rank ordering between the two wear models. For example, Equia Forte demonstrated lower generalized wear resistance compared to the other materials, while localized wear for Equia was higher. The mechanism of reinforcement of Equia is based on the incorporation of evenly dispersed, highly reactive ultrafine glass particles and the use of a higher molecular weight polyacrylic acid.[41] A recent study reporting the loss modulus and loss tangent values for Equia Forte[32] suggested these material properties would favor energy dissipation within the material and thus resistance to highly concentrated contact forces. On the other hand, the higher generalized values for Equia could be attributed to a less robust integration of the fillers in the polyacrylic continuous phase, leading to more erosive material loss.

There is an even greater discrepancy for Activa between the two wear models. While showing good resistance to generalized wear, Activa generated the highest localized volume loss of all the materials tested. Activa uses a unique continuous-phase resin, termed an "ionic resin", which is stated to contain a small amount of water.[42] While several studies have shown higher flexural strength, compressive strength, and flexural fatigue for Activa compared to glass ionomer and resin-modified glass ionomers,[6,11] one study revealed a much higher deflection at break compared to a glass ionomer, a resin-modified glass ionomer, and a resin composite.[8] This higher deflection at break might be attributed to the aqueous ionic resin in the continuous phase. The localized wear data could be a result of this low resistance to deflection under the high point load inherent in the contact of the localized stylus on the material surface. The localized wear behavior might be affected by irreversible plastic deformation due to the properties of the polymer matrix.

The wear of the traditional resin-modified glass ionomer (RMGIC) was significantly higher than the conventional glass ionomer and the self-adhesive hybrid resin material. This is likely due to the differences in the matrix composition. The set RMGIC material, Fuji II LC, has a cross-linked polyalkenoate network mixed with the polymer chains of the HEMA monomer. It is likely that the coherence of filler particles embedded in this matrix is inferior to that of the fillers in the conventional glass-ionomer matrix. The nearly two-fold difference in wear between the RMGIC and the conventional GIC (Equia Forte) in the current investigation was also observed in a study using a different wear simulation model.[38]

The wear values generated in this study compare favorably to previous data generated under the same experimental conditions in our laboratory for resin composite restoratives. In particular, with respect to generalized wear, ASAR-MP4/LC and SC as well as Activa exhibited generalized wear similar to that of Z-250[4] and Filtek Supreme Ultra[33] (3M Oral Care; St Paul, MN, USA). In a third study in our laboratory,[3] the resin composite SonicFil (Kerr; Orange, CA USA) generated similar localized wear and higher generalized wear compared to the Equia Forte and ASAR-MP4 data reported here. In that same investigation, the generalized wear data was higher for Herculite Ultra (Kerr), Tetric EvoCeram Bulk Fill (Ivoclar Vivadent; Schaan, Liechtenstein), Esthet-X (Dentsply Sirona), Venus Diamond (Heraeus Kulzer; Hanau, Germany), and SonicFil compared to the values for Activa, Equia Forte, and ASAR-MP4 in the current report. While not definitive, the similarity of the in vitro localized and generalized wear values of ASAR-MP4 to Equia Forte may suggest acceptable clinical performance with respect to the wear of this material when compared to the clinical evidence for Equia Forte. In the same way, the similarity of wear values for the self-adhesive materials tested in this study to the wear values for resin composites in previous investigations would indicate the strong potential for these materials to be used in posterior stress-bearing areas. Additional clinical investigations are needed to evaluate the clinical utility and performance of these self-adhesive restoratives in permanent posterior teeth.

Both null hypotheses were rejected, as there were statistical differences in both localized and generalized wear among the materials tested in this study.

CONCLUSION

The localized and generalized wear (volume loss) of the materials tested was found to vary depending upon the mater-

ial system. The newly developed self-adhesive composite hybrid generated values in both wear challenges similar to those of a glass ionomer, resin-modified glass ionomer, and bioactive resin-modified glass ionomer.

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Clinical relevance: The in vitro wear resistance of a newly developed self-adhesive composite hybrid may suggest equal or better clinical performance than that of glass ionomer and resin-modified glass ionomer restorative materials used in posterior restorations.