Amalgam Alternatives Critically Evaluated: Effect of Long-term Thermomechanical Loading on Marginal Quality, Wear, and Fracture Behavior

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Purpose: This in vitro study evaluated marginal integrity, 2-body wear, and fracture behavior of an array of bonded and nonbonded posterior restorative materials after thermomechanical loading (TML).

Materials and Methods: Eighty-eight MOD cavities with one proximal box beneath the CEJ were prepared in extracted human third molars according to a well-established protocol. Direct restorations were made using the following materials: amalgam (Dispersalloy), Ketac Molar Quick, Surefil One (with or without light curing), Activa, AdheSE Universal/Heliomolar, Fuji II LC improved, Equia Forte, Scotchbond Universal/Filtek Supreme, Xeno V+/CeramX.mono+, Prime&Bond active/Spectra ST CeramX HV, Prime&Bond elect/Spectra ST CeramX HV. Before and after thermomechanical loading (2500/5000/12,500 thermocycles between 5°C and 55°C + 100,000/200,000/500,000 x 50 N), marginal gaps and 2-body wear depths were analyzed on epoxy resin replicas using SEM and CLSM. Fractures were observed under a light microscope (20X). Results were analyzed with Kruskal-Wallis and Mann-Whitney U-tests ($p < 0.05$).

Results: For marginal quality, Surefil One showed promising in vitro behavior close to that of resin composite bonded with a self-etch adhesive ($p > 0.05$). For wear, amalgam and resin composites with recent filler technology were still superior ($p < 0.05$), but Surefil One LC outperformed Activa, Ketac Molar Quick, Equia Forte Fil, and Fuji II LC ($p < 0.05$). When Surefil One was occlusally light cured, no fractures occured, even after 500,000 cycles of TML.

Conclusion: The novel self-adhesive posterior restorative Surefil One did not exhibit superior outcomes for all evaluated aspects. However, it showed stable fracture behavior, good marginal quality, and acceptable wear resistance in vitro.

Keywords: amalgam alternatives, resin composites, resin-modified glass-ionomer cements, self-adhesive materials.

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Irrespective of whether dental amalgam is undergoing phase-out or phase-down, it is simply not likely to prevail beyond 2030 as a direct restorative material.[4,25] Moreover, although the restoration of minimally invasive restorations is not completely impossible when amalgam is used, it still represents "extension for prevention", which may no longer

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Table 1 List of materials and protocol specifics

Restorative	EXP	Lot	Adhesive	EXP	LOT	Specifics
Dispersalloy	2020-10	000023	N/A			Harvard Cement lining
Activa Restorative	2019-08	170819	N/A			4 mm LC
Ketac Molar Quick	2019-01	570386	N/A			SC
Surefil One LC*	2019-07	1807004175	N/A			LC*
Surefil One SC						SC
Ceram.x mono+ M2	2019-07	1708000336	XenoV+	2019-01	1701003101	Self-etch
Ceram.x universal A2	2019-10	1711000231	Prime&Bond active	2019-09	1712000006	Self-etch
			Prime&Bond elect	2020-10	171004	Self-etch
Equia Forte A2	2019-08	170807A	N/A			Bulk fill SC
Filtek Supreme Body A2	2020-03	N884641	Scotchbond Universal	2019-06	3173109	Self-etch
Fuji II LC Improved A2	2019-07	170713A	N/A			1.8 mm LC
Heliomolar A2	2021-09	W83730	Adhese Universal Viva Pen	2019-05	W34082	Self-etch

LC*: light curing of occlusal surface after bulk filling; SC: self-curing.

be considered adequate in most clinical cases.[23] Today, minimally invasive restorations are ideally made of bonded resin-based composites.[26-28] Working with the latter, the influence of the operator and patient is tremendous, but also long-term adhesion to enamel and dentin as well as the occlusal stability of these bonded dental biomaterials are key factors for clinical success.[33,34] Insufficient adhesion cannot counteract both initial and residual polymerization stresses and leads to gap formation, leakage, recurrent caries, pulpal irritation, and retention loss.[30-32] Therefore, a tight marginal seal must still be the primary goal for the clinician, because once it occurs, gap formation is not reversible even with restorative materials that claim to prevent demineralization along cavity margins.[1,3,9,17,18]

Despite several innovative developments in the field of adhesives, a 100% gap-free margin is not realistically achievable. For a long time, multi-step adhesives have been repeatedly reported to provide clinically proven, successful, durable adhesion to enamel and dentin,[9,33,34] while simplified adhesives performed worse in vitro and in vivo.[9,34] Although the latest generation of universal adhesives seem to have disproven the claim that simplification always reduces performance, a certain amount of technique sensitivity is still involved, albeit reduced, when teeth are bonded with adhesives of all kinds.[8,33,34]

Simplifications of resin composite materials have been less frequently reported during the last decade in adhesive dentistry. There has definitely been improvement in the field of polymerization shrinkage and wear resistance, but a meticulous incremental layering technique was mandatory to meet the above-mentioned prerequisites for effective long-term sealing of resin composite restoration margins.[21] Bulk-fill flowable and sculptable composites have changed several clinical protocols by allowing a 4-mm bulk placement in one layer; in most cases, however, it is necessary to cover them with a 2-mm layer of conventional resin composite.

It does not follow that when amalgam use becomes less frequent, bonded resin composites and especially bulk-fill composites represent a true substitute due to their faster application, because the fundamental difference between amalgam and resin composite is the latter's sensitivity to contamination with saliva or blood.[8,21] Therefore, a desperate need still exists for easy-to-use amalgam substitutes, ie, other than bonded resin composites.[25] The logical next step in simplification and reduction of technique sensitivity would be self-adhering tooth-colored materials. Due to the introduction of a novel self-adhesive posterior material and the lack of in vitro data for classic amalgam alternatives such as glass ionomers, glass hybrids, and resin-modified glass-ionomer cements, the objective of the present study was to compare several posterior biomaterials in a Class II fatigue-loading design in terms of marginal quality, wear behavior, and fracture resistance.

The null hypothesis tested was that the self-adhesive composite hybrid would perform equally to different posterior materials regarding (1) marginal quality in enamel and dentin, (2) wear resistance, and (3) fracture behavior in vitro.

MATERIALS AND METHODS

Ninety-six intact, noncarious, unrestored human third molars extracted for therapeutic reasons with the informed consent of the patients were stored in an aqueous solution

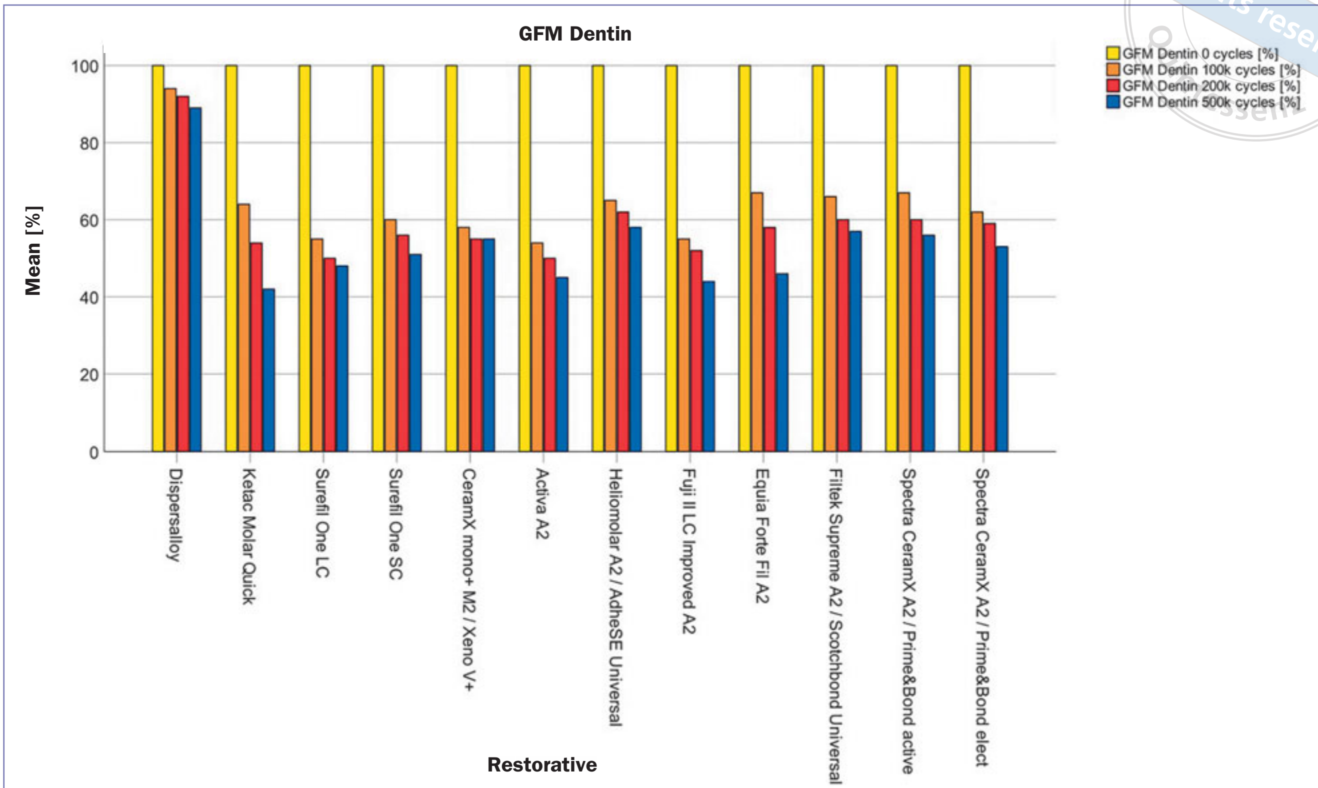

Fig 1 Gap-free margins (GFM) in enamel (mean values; for detailed information with statistical subgroups, see Table 2).

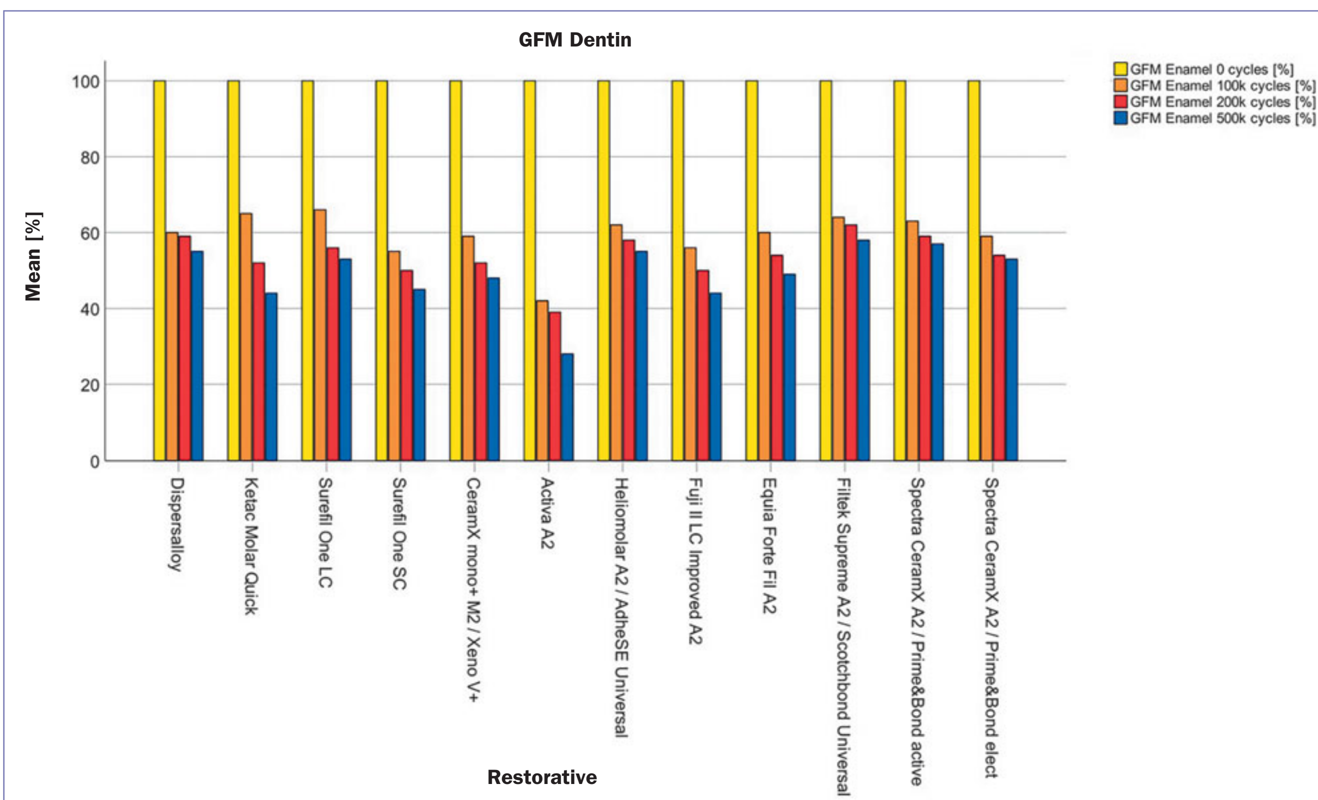

Fig 2 Gap-free margins (GFM) in dentin (mean values; for detailed information with statistical subgroups, see Table 2).

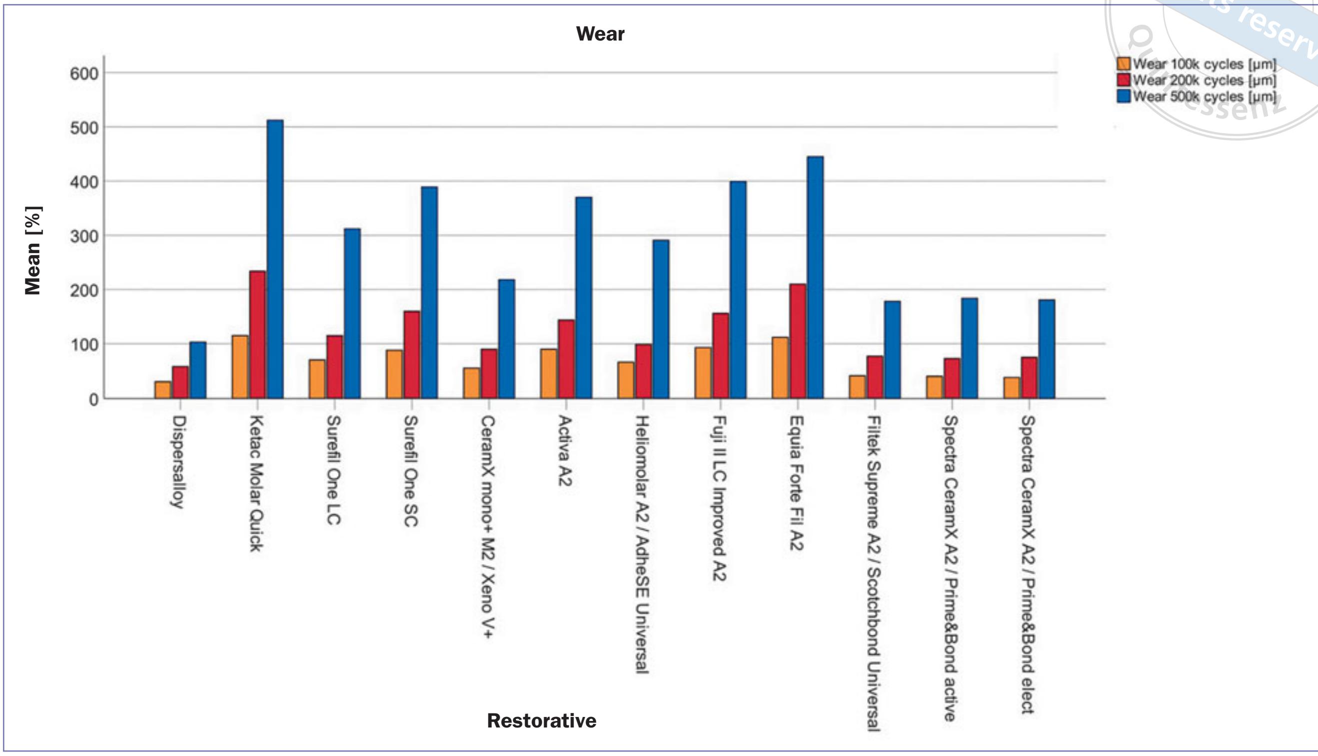

Fig 3 Mean wear values as vertical height loss in occlusal contact areas (for detailed information with statistical subgroups, see Table 2).

of 0.5% chloramine T at 4°C for up to 30 days. The present laboratory study was approved by a local ethics committee (University of Giessen, AZ 143/09). The teeth were debrided of residual plaque and calculus, and examined to ensure that they were free of defects under a light microscope at 20X magnification.

Class II cavities were prepared (MOD, buccolingual width 4 mm, depth 2 mm at the bottom of the proximal box, slight undercuts) with the distal proximal margin located 1-2 mm below the cementoenamel junction (n = 8). The cavities were cut using coarse diamond burs under profuse water cooling (80-µm diamond, Komet; Lemgo, Germany), and finished with a 25-µm finishing diamond (one pair of diamonds per four cavities). Inner angles of the cavities were rounded and the margins were not bevelled to deliver results comparable to those of previous experiments. The standardized size of the cavities was controlled with Cerec 3D scans (Sirona; Bensheim, Germany). Eight teeth were randomly selected for each filling material. Resin composites were polymerized with a Smartlite Focus light-curing unit (Dentsply Sirona; Konstanz, Germany). The intensity of the light was checked periodically with a radiometer (Demetron Research; Danbury, CT, USA) to ensure that 800 mW/cm^2 was always delivered during the experiments.

Cavities were surrounded with a metal matrix band, and restored in bulk or horizontal increments (Table 1). The increments were separately light cured for 20 s each with the light source in contact with the coronal edge of the matrix band. Prior to the finishing process, visible overhangs were removed using a posterior scaler (A8 S204S, Hu-Friedy; Leimen, Germany). Proximal margins were finished with flexible disks (SofLex Pop-on, 3M Oral Care; St Paul, MN, USA). Amalgam restorations were manually condensed after placing a lining of Harvard Cement (with lines drawn in pencil in the cavities to ensure equal cement thickness), then polished after 24 h. The specifics of the different materials are displayed in Table 1.

After storage in distilled water at 37°C for 21 days according to a well-established protocol guaranteeing no further water sorption that would falsify results,[9] impressions (Provil Novo, Heraeus Kulzer; Hanau, Germany) of the teeth were taken and a first set of epoxy resin replicas (Alpha Die, Schuetz Dental; Rosbach, Germany) was made for SEM evaluation. Specimens were thermomechanically loaded in an artificial oral environment (CS4 professional line and THE 1100, SD Mechatronik; Feldkirchen, Germany). Two specimens were arranged in one simulation chamber and occluded against a steatite (a multi-component semi-porous crystalline ceramic material) antagonist (6 mm in diameter) contacting two lateral ridges of restorations for 100,000 cycles at 50 N at a frequency of 0.5 Hz. The specimens were simultaneously subjected to 2500 thermocycles between +5°C and +55°C by filling the chambers with water of each temperature for 30 s. Further, also 200,000 and 500,000 mechanical cycles as well as 5000 and 12,500 thermocycles were applied. The mechanical action and the

Table 2 Synopsis of results with final significance levels after 500,000 cycles (GFM: gap-free margins)

Adhesive	Restorative	GFM Enamel 0/100k/200k/500k % (SD)	GFM Dentin 0/100k/200k/500k % (SD)	Wear 100k/200k/500k µm (SD)	Fractures after no. of cycles
–	Dispersalloy	100/60(7)/59(8)/55(9)^{A}	100/94(3)/94(4)/92(4)/89(5)^{A}	30(4)/58(6)/103(11)^{A}	0
–	Ketac Molar Quick	100/65(9)/52(7)/44(12)^{C}	100/64(9)/54(14)/42(15)^{C}	115(23)/234(43)/512(56)^{H}	4 chippings 64,922 89,003 156,553 178,903 2 bulk fractures 345,502 399,040
–	Surefil One LC	100/66(14)/56(14)/53(17)^{B}	100/55(10)/50(10)/48(15)^{B}	70(16)/115(20)/312(16)^{D}	0
–	Surefil One SC	100/55(9)/50(9)/45(10)^{C}	100/60(11)/56(9)/51(11)^{B}	88(18)/160(21)/389(14)^{F}	2 chippings 189,101 345,002
Xeno V+	CeramX mono+ M2	100/59(9)/52(11)/48(12)^{BC}	100/58(6)/55(9)/55(10)^{B}	55(9)/90(10)/218(19)^{C}	0
–	Activa A2	100/42(14)/39(16)/28(11)^{D}	100/54(12)/50(11)/45(12)^{C}	90(12)/144(21)/370(38)^{F}	2 chippings 121,200 209,993
AdheSE Universal	Heliomolar A2	100/62(6)/58(10)/55(9)^{A}	100/65(10)/62(12)/58(9)^{B}	66(16)/99(23)/291(30)^{D}	1 chipping 345,609
–	Fuji II LC Improved A2	100/56(10)/50(12)/44(8)^{C}	100/55(12)/52(10)/44(11)^{C}	98(13)/156(21)/399(42)^{F}	1 chipping 89,340
–	Equia Forte Fil A2	100/60(9)/54(12)/49(14)^{B}	100/67(10)/58(11)/46(14)^{C}	112(21)/210(28)/445(51)^{G}	2 chippings 89,430 94.323 2 bulk fractures 402,908 405,221
Scotchbond Universal	Filtek Supreme A2	100/64(5)/62(8)/58(10)^{A}	100/66(8)/60(10)/57(8)^{B}	41(7)/77(9)/178(21)^{B}	0
Prime&Bond active	Spectra CeramX A2	100/63(6)/59(7)/57(8)^{A}	100/67(7)/60(8)/56(7)^{B}	40(9)/73(12)/184(23)^{B}	0
Prime&Bond elect	Spectra CeramX A2	100/59(10)/54(8)/53(12)^{A}	100/62(8)/59(7)/53(10)^{B}	38(6)/75(10)/181(19)^{B}	0

Different superscript letters indicate statistically significant differences.

water temperature inside the chewing chambers were checked periodically to ensure a reliable thermomechanical loading (TML) effect.

After completion of each loading cycle, impressions of the teeth were made again and another set of replicas was made for each restoration. The replicas were mounted on aluminum stubs, sputter-coated with gold, and examined in an SEM (Phenom, FEI; Amsterdam, The Netherlands) as before at 200X magnification. SEM examination was performed by one operator experienced in quantitative margin analysis, who was blinded to the restorative procedures. The marginal integrity between resin composite and dentin was expressed as a percentage of the entire margin length in enamel and dentin. Marginal qualities were classified according to the criteria “gap-free margin”, “gap/irregularity” and “not assessable/artefact” (Figs 4-10). Afterwards the percentage “gap-free margin” in relation to the individual assessable margin was calculated as marginal integrity. Wear analysis was carried out using the same replicas under a confocal scanning laser microscope (CSLM; VK-X 100, Keyence; Neu-Isenburg, Germany), where vertical height loss was measured to an accuracy of 0.1 micrometers by superimposition. Fractures were visually analyzed under an OpMicroscope (Zeiss OpMi; Jena, Germany) (Fig 11).

Statistical analysis was performed using SPSS/PC+, Version 12 (SPSS; Chicago, IL, USA) for Windows. As the majority of groups in each of the two investigations (ie, enamel or dentin marginal integrity) did not exhibit normal data distribution (Kolmogorov-Smirnov test), non-parametric tests were used (Kruskal-Wallis test, Wilcoxon matched-pairs signed-ranks test, Mann-Whitney U-test) for pairwise comparisons at the 95% significance level regarding the variables “percentage of gap-free margins”, “wear depth”, and “occurrence of fractures”.

Table 3 Results after 100,000 cycles

Adhesive	Restorative	GFM enamel % (SD)	GFM dentin % (SD)	Wear µm (SD)
–	Dispersalloy	$60(7)^{AB}$	$94(3)^{A}$	$30(4)^{A}$
–	Ketac Molar Quick	$65(9)^{A}$	$64(9)^{B}$	$115(23)^{G}$
–	Surefil One LC	$66(14)^{A}$	$55(10)^{C}$	$70(16)^{D}$
–	Surefil One SC	$55(9)^{B}$	$60(11)^{BC}$	$88(18)^{F}$
Xeno V+	CeramX mono+ M2	$59(9)^{B}$	$58(6)^{C}$	$55(9)^{C}$
–	Activa A2	$42(14)^{D}$	$54(12)^{C}$	$90(12)^{F}$
AdheSE Universal	Heliomolar A2	$62(6)^{A}$	$65(10)^{B}$	$66(16)^{D}$
–	Fuji II LC Improved A2	$56(10)^{B}$	$55(12)^{C}$	$98(13)^{F}$
–	Equia Forte Fil A2	$60(9)^{AB}$	$67(10)^{B}$	$112(21)^{G}$
Scotchbond Universal	Filtek Supreme A2	$64(5)^{A}$	$66(8)^{B}$	$41(7)^{B}$
Prime&Bond active	Spectra CeramX A2	$63(6)^{A}$	$67(7)^{B}$	$40(9)^{B}$
Prime&Bond elect	Spectra CeramX A2	$59(10)^{AB}$	$62(8)^{B}$	$38(6)^{B}$

Different superscript letters within columns indicate statistically significant differences ($p < 0.05$).

Table 4 Results after 200,000 cycles

Adhesive	Restorative	GFM enamel % (SD)	GFM dentin % (SD)	Wear µm (SD)
–	Dispersalloy	$59(8)^{A}$	$92(4)^{A}$	$58(6)^{A}$
–	Ketac Molar Quick	$52(7)^{B}$	$54(14)^{BC}$	$234(43)^{H}$
–	Surefil One LC	$56(14)^{A}$	$50(10)^{C}$	$115(20)^{E}$
–	Surefil One SC	$50(9)^{B}$	$56(9)^{BC}$	$160(21)^{F}$
Xeno V+	cx mono+ M2	$52(11)^{B}$	$55(9)^{BC}$	$90(10)^{C}$
–	Activa A2	$39(16)^{C}$	$50(11)^{C}$	$144(21)^{G}$
AdheSE Universal	Heliomolar A2	$58(10)^{A}$	$62(12)^{B}$	$99(23)^{D}$
–	Fuji II LC Improved A2	$50(12)^{B}$	$52(10)^{C}$	$156(21)^{H}$
–	Equia Forte Fil A2	$54(12)^{AB}$	$58(11)^{B}$	$210(28)^{I}$
Scotchbond Universal	Filtek Supreme A2	$62(8)^{A}$	$60(10)^{B}$	$77(9)^{B}$
Prime&Bond active	cx universal A2	$59(7)^{A}$	$60(8)^{B}$	$73(12)^{B}$
Prime&Bond elect	cx universal A2	$54(8)^{A}$	$59(7)^{B}$	$75(10)^{B}$

Different superscript letters within columns indicate statistically significant differences ($p < 0.05$).

RESULTS

The results of the different subinvestigations are displayed in Tables 2 to 4 and Figs 1 to 3. In terms of marginal quality, amalgam revealed effects of thermomechnical loading over time, especially in enamel ($p < 0.05$, Table 2, Fig 1), and Surefil One showed in vitro behaviour similar to that of conventional resin composite when bonded with self-etch adhesives ($p > 0.05$, Figs 1 to 3). Amalgam showed the best wear resistance in the present investigation ($p < 0.05$). Resin composites with recent filler technology exhibited superior wear behavior compared to simplified amalgam substitutes ($p < 0.05$), however, light-cured Surefil One outperformed Activa, Equia Forte Fil, and Fuji II LC ($p < 0.05$, Fig 12). Regarding fracture behavior, glass hybrid and resin-modified glass-ionomer cements suffered more fractures than did amalgam and resin-based composites ($p < 0.05$), with the exception of Heliomolar. When Surefil One was occlusally light cured, no fractures occured.

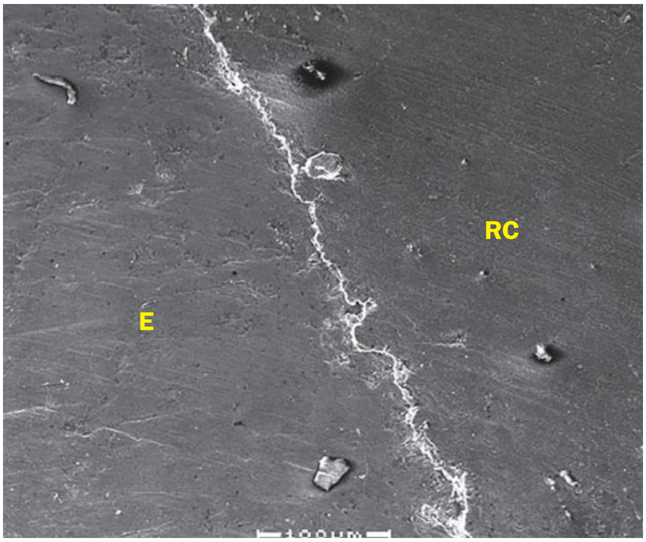

Fig 4 SEM image showing marginal quality. The margin between enamel (E) and resin composite (RC) is slightly irregular but gap free (Prime&Bond active / Spectra CeramX HV after 100,000 TML cycles; original magnification 200X).

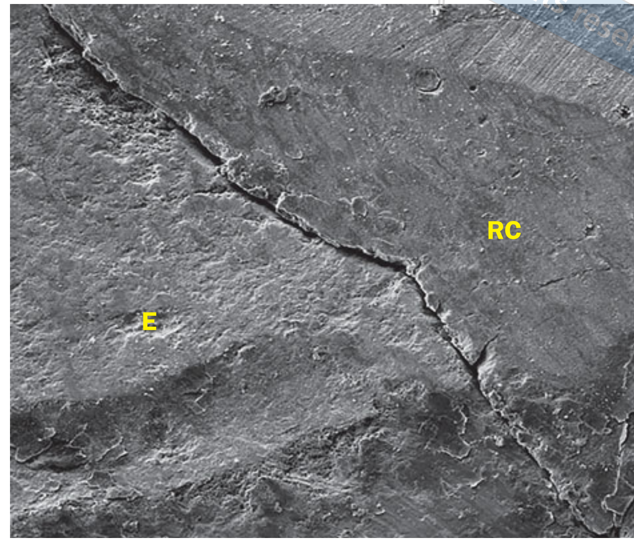

Fig 5 SEM image of the margin between enamel (E) and resin composite (RC) shows gap formation characteristic of occlusal self-etch bond degradation in enamel after 500,000 cycles (original magnification 200X).

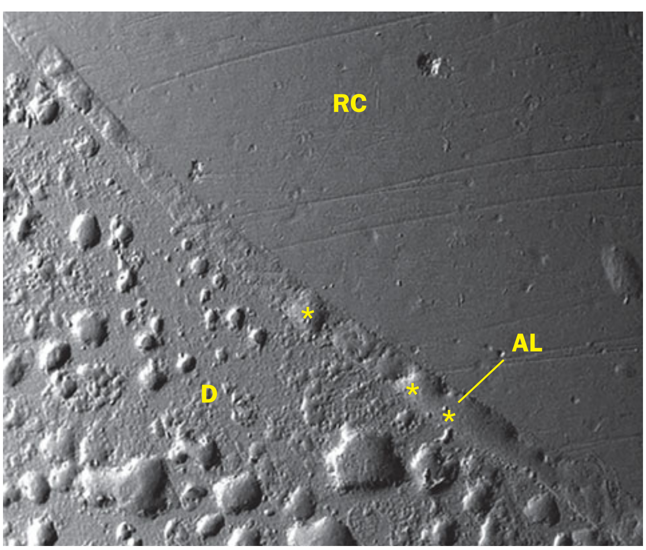

Fig 6 SEM image of characteristic dentin margin after 200,000 cycles. The adhesive layer (AL) shows hygroscopic swelling, which in some areas is more pronounced (asterisks). Water droplets in dentin (D) were visualized by the replica technique (original magnification 200X).

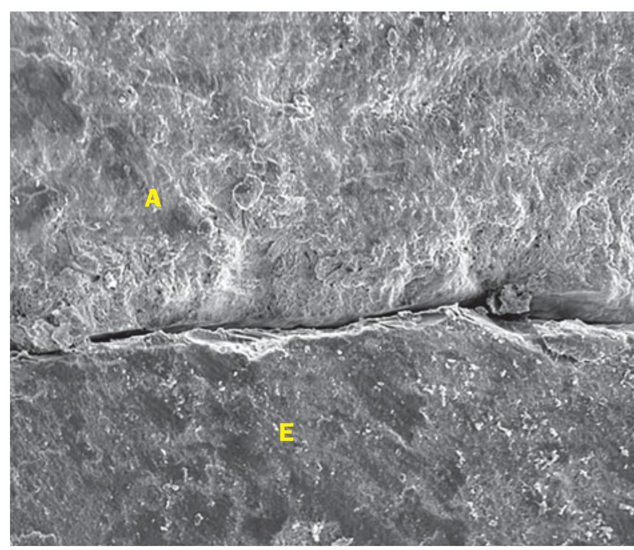

Fig 7 SEM image of marginal quality. The margin between enamel (E) and Activa (A) is broken down after 100,000 cycles (original magnification 200X).

DISCUSSION

The ideal restorative biomaterial for restoring carious lesions must at least be stable, durable, and biocompatible;[6,10,11] at best it would also provide remineralization and a cariostatic effect. It has been repeatedly reported that patient factors show a substantial influence on the clinical behavior of restorations; hence, an amalgam substitute should also be easy to use and robust in terms of many parameters, without substantial flaws. Amalgam is still widespread because it is easy to handle, less technique sensitive than any bonded material, and inexpensive.[4] However, mercury pollution issues moreso than health hazards will at some point terminate the used of amalgam, irrespective of the fact that it still is a solid restorative material.[4,25]

Several posterior biomaterials that have been introduced as amalgam substitutes have failed, either because they are too technique sensitive – such as bonded resin-based composites (independent of layer thickness)[21] – or too weak for heavily loaded posterior teeth with larger cavities.

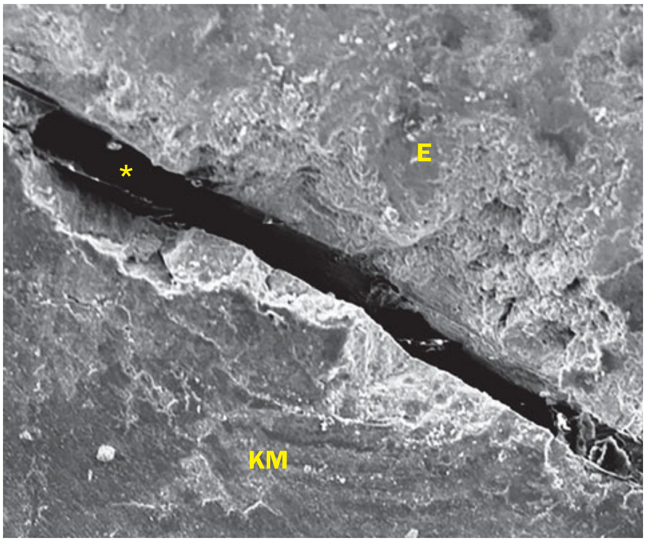

Fig 8 SEM image of marginal quality: The margin between enamel (E) and Ketac Molar (KM) is heavily disrupted after 100,000 cycles (original magnification 200X).

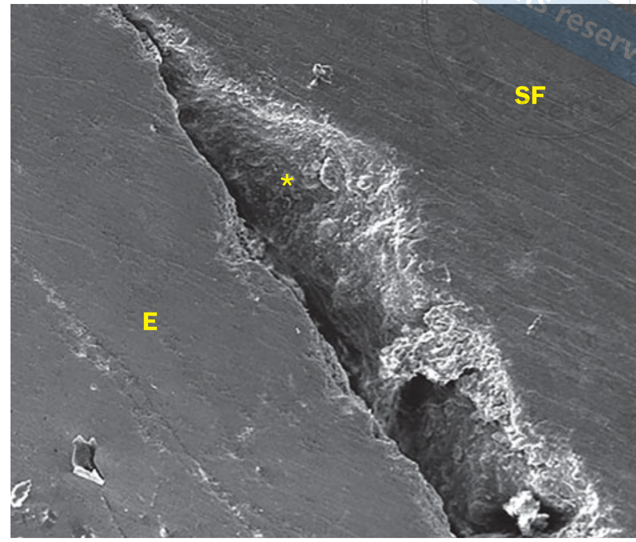

Fig 9 SEM image of marginal quality shows chipping in Surefil One SC (SF) at an enamel margin (E) after 100,000 cycles (original magnification 200X).

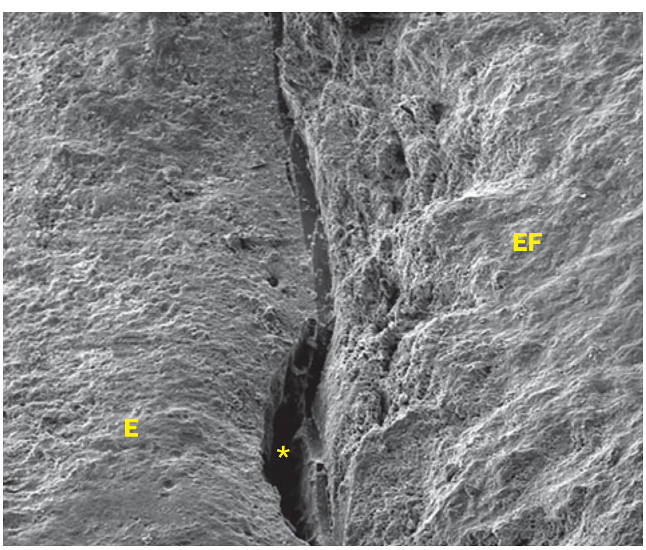

Fig 10 SEM image of marginal quality showing enamel (E) chipping in an Equia Forte (EF) specimen after 500,000 cycles (original magnification 50X).

Although these weaker materials, eg, glass-ionomer cements, resin-modified glass-ionomer cements, or glass hybrids,[5] have shown some “borderline durability” in recent clinical studies,[13,14] none of them is fully accepted for posterior use. Although it may be considered unfair to include several groups of materials in the present thermomechanical loading scenario, clinical simulation data are both scarce and important for any preclinical screening.[9]

Any innovative evolution of amalgam alternatives would have to provide either less technique-sensitive bonding approaches (and perhaps be relatively contamination insensitive), comprise considerably strengthened glass-ionomer-like materials, or consist of a completely new class of materials combining the two. Looking back on more than two decades of research on bonded and nonbonded amalgam alternatives, dramatical clinical failures of bioactive materials of the past and present have clearly demonstrated that a true amalgam replacement material is not easy to make.[15] Ariston pHc (pH control) was the first bioactive posterior material which was not bonded. It was indicated for cavities with undercuts and it was stipulated that any marginal gap would be managed by fluoride and calcium release as “pH control”.[35] Indeed, some in vitro studies showed that there was practically no adhesion and that substantial amounts of ions were released inside the gaps.[30] Finally, clinical outcome was poor because ion release was apparently accompanied by hygroscopic expansion, which was responsible for high tooth fracture rates.[15] Fifteen years later, the “next” bioactive material was marketed with similar claims and procedures, such as omission of cavity pretreatment. However, also in that case early clinical results disproved initial marketing claims with inacceptable retention loss already in early stages of a clinical trial[32](Table 2, Fig 4). Therefore, one may argue that the field of cost-effective amalgam replacement material evolution has discouraged many manufacturers from pursuing this.

In this study, an array of different amalgam replacement strategies was thoroughly evaluated under simulated clinical conditions. Three clinically crucial and relevant parameters were investigated, ie, marginal quality, wear resistance, and fracture behavior, before and after thermomechanical loading.[29] Although clinical trials remain the ultimate instrument in evaluating the performance of dental materials,[24,26-28,31-33] it must be taken into account that the individual product under investigation may not be up to date or

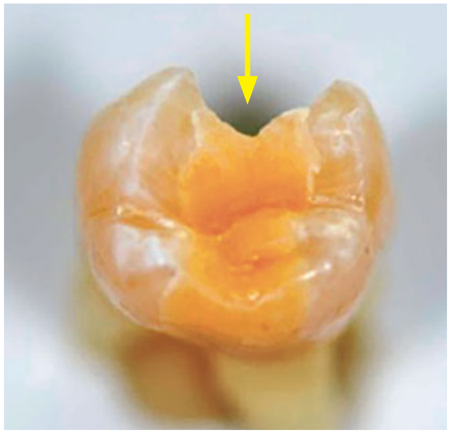

Fig 11 Bulk fracture in a Ketac Molar specimen after 89,003 thermomechanical cycles.

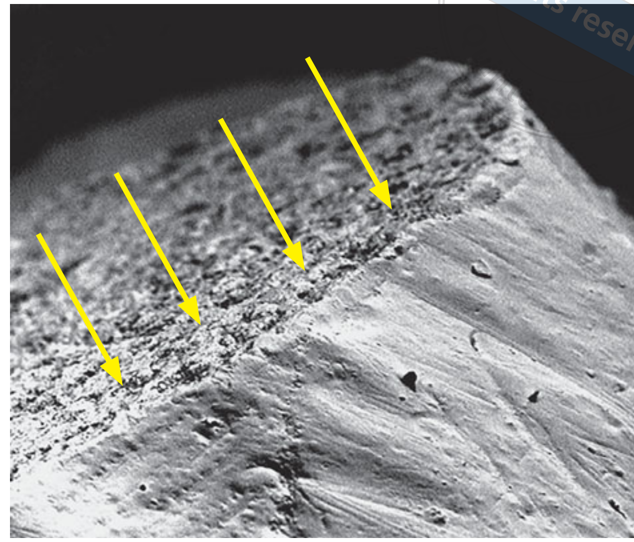

Fig 12 Wear resistance: distinct 2-body wear facet in an Equia Forte specimen after 500,000 cycles (original magnification 50X).

even available by the time useful clinical data have been collected.[15-17] Thus, preclinical screening via laboratory tests is still an important tool for the evaluation of dentin adhesives; it allows evaluating a greater number of experimental groups than is feasible in clinical studies, where the number of variables must be minimized.[27]

There are many different approaches to predicting clinical behavior of dental biomaterials in the laboratory. Bond strength tests are commonly carried out with quasistatic load until fracture.[33] However, the failure of clinical restorations due to high loads is exceptional and primarily observed in root canal treated teeth. Under clinical conditions with vital teeth, materials or interfaces fail after repeated subcatastrophic loading with stresses being too small to provoke spontaneous failures.[10,11] As a result, after months and years of clinical service, the most frequent observation is gap formation between resin composite and tooth substrates.[18,22] Gap formation may occur at the margins in enamel and dentin as well as along the resin-dentin interface as loss of internal adaptation. These gaps result from either insufficient compensation for initial polymerization shrinkage stresses prior to the first occlusal loading, or from repeated subcritical stresses below the maximum stress the adhesive restoration can resist.[33,34] As a consequence, in vitro fatigue tests provide a better understanding of the in vivo behaviour of adhesion to both enamel and dentin.[11,12]

The results of this study revealed that the adhesive performance of the self-adhering materials was comparable to conventionally bonded resin composites when self-etch adhesives are used for bonding (Tables 2 to 4, Figs 1 to 3). Depending on cavity size and presence of bevelled margins, paramarginal enamel fractures are normally observed in this kind of preclinical investigation.[11] Due to this study's different adhesive approach, this was not observed at all (Figs 8 to 11).

The results of the bonded resin-based composites under investigation were not surprising at all, as many in vitro studies have displayed a certain range of values which could be interpretable as clinically acceptable or not.[9,11] Although direct comparison between marginal quality data in vitro and in vivo is possible to only a limited extent, some studies have shown that these things are quite predictable in the lab.[7,10] Due to its easier handling, only the self-etch approach was followed in enamel and dentin in the present study. However, it is obvious from previous results of our group using identical laboratory conditions that the etch-and-rinse technique would have produced higher percentages of gap-free margins in enamel compared to all material combinations of the present investigation.[9,29]

The effect of thermomechanical loading on nonbonded or chemically bonded materials has not been intensively studied so far and may also not have been fully understood (Fig 5). However, it is interesting that Ketac Molar, for instance, behaved showed almost completely identical behavior in vitro and in vivo: clinically, we detected a 35% fracture rate of Ketac Molar after two years of clinical service, and in vitro we found 37.5% fractures using the present thermomechanical loading scenario (Fig 8).[5] Another interesting finding is that Heliomolar, a microfilled resin composite with comparatively poor, previous lab performance, also suffered some fractures after long-term thermomechanical loading.[2] Although the present evaluation obviously lacks clinically relevant contamination and microbiological factors, it seemed to be able to mimic biomechanical clinical circumstances quite well (Figs 9 to 11).

The two-body wear experiment revealed considerable differences regarding in vitro wear resistance. It was clearly demonstrated that amalgam is still superior to all other materials examined, which is not surprising due to its metallic nature. It was also clearly shown that the resin-based materials outperformed the different cement types, but with significant differences between each other regarding wear resistance (Figs 11 and 12). The difference regarding wear of amalgam vs resin composite is somewhat more pronounced than reported previously, but still encouraging.[19] It is hard to estimate clinical behavior from the results of this study alone, but it could be difficult to guarantee durable vertical stability when cement-based amalgam replacement materials are used clinically in stress-bearing posterior areas. In these terms, resin-based composites as well as the new self-adhesive composite hybrid performed better.

CONCLUSION

The present investigation revealed considerable biomechanical differences of the materials under investigation regarding marginal quality, wear resistance, and fracture behavior. The null hypothesis had to be rejected. To verify the present data, additional evaluations of internal adaptation especially for nonbonded materials as well as clinical data are necessary.

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Clinical relevance: In terms of relative insensitivity to technique, no valid substitute for amalgam seems to exist to date. The new self-adhesive restorative showed acceptable results regarding all tested in vitro parameters.