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Repair bond strength of dental composites: systematic review and meta-analysis

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ABSTRACT

This study investigated by means of a systematic review of the literature and meta-analysis the impact of physical and/or chemical surface treatments on the repair bond strength of methacrylate-based dental composites. Three international databases (Medline/PubMed, Scopus, and Web of Science) were searched. Studies that evaluated the repair bond strength of aged control composites (untreated or treated with abrasives) and aged composites subjected to surface treatments before repair (physical, chemical, or physical + chemical) were included. In total, 777 articles were found, 129 were selected for full-text reading, and 15 studies were included in the qualitative and quantitative synthesis. Meta-analyses were conducted using random effects model to calculate pooled mean differences between control and treated composites, according to the different groups of surface treatments. Statistical heterogeneity was assessed using the Cochrane Q statistic and I^2 test. Risk of bias of all included studies was assessed. Application of chemical or physical + chemical surface treatments of aged composites was shown to generally improve their repair bond strengths. Silane coupling agents appeared to have a minor role as compared to adhesive agents in improving repair potential. Airborne-particle abrasion alone was found not to contribute significantly to the repair bond strengths. High heterogeneity was observed in most statistical analyses; the analysis of risk of bias also indicated potential problems associated with reporting in the studies. Therefore, suggestions for future *in vitro* studies on the repair bond strength of dental composites are given.

Contents

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1. Introduction

Resin-based dental composites are the materials of choice for restoring anterior and posterior teeth. The annual failure rates of anterior and posterior composite restorations commonly vary between 1% and 4% [1–3]. Patient characteristics, professional technique and experience, and material selection are factors known to potentially affect the clinical performance of dental restorations [4]. Restorations in patients with higher risk for caries lesions or occlusal stresses, for instance, are expected to show increased failure rates [5,6].

In case of composite restoration failures, the dentist has three main options to deal with the defective restoration: to refurbish, repair, or replace the composite [7–9]. Refurbishing means that no material or dental structure will be removed and additional restorative material will be added to fix the restoration: refinishing and repolishing are carried out to improve anatomy and surface properties. Repair is a procedure that involves partial removal of the defective part of the restorative, which is then repaired with new material to complete the restoration. In contrast to refurbishing and repairing, which might be considered more conservative approaches [9], replacing a restoration involves complete removal of the restorative (even portions that might appear clinically acceptable) for placement of new material. In this approach, it is virtually impossible to avoid removal of sound tooth structure during cavity preparation [10], increasing the risk of pulp injury, tooth fracture, and even need for endodontic treatment.

Studies have shown that composite repairs might improve the clinical longevity of dental restorations [7,9,11,12]. However, there is no gold standard protocol or materials established for treating the aged composite surfaces before repair. Despite the fact that surface treatments before repair are not the focus of clinical studies, the literature is abundant with laboratory evidences on different approaches to improve the repair potential of composites. These studies usually include evaluation of physical, chemical, or association between physical and chemical treatments of the composite seeking improved repair bonding. Physical treatments have the ultimate goal to improve mechanical keying between the aged and new (repair) composite, whereas chemical agents are applied in an endeavor to improve chemical coupling between resin-based materials at the adhesive interface.

The high variability of materials, techniques, and testing methods used in laboratory investigations regarding surface treatments of dental composites before repair sometimes hinder comparisons among studies. Summarization of *in vitro* findings, associated with an overall analysis of variables affecting the repair potential, might help elucidating whether physically or chemically treating the composites surfaces before repair is valuable. Therefore, this study was designed to evaluate by means of a systematic review of the literature and meta-analysis the impact of physical and/or chemical surface treatments on the repair bond strength of methacrylate-based dental resin composites.

2. Materials and methods

This systematic review was carried out according to the guidelines of Cochrane Handbook for Systematic Reviews of Interventions [13], following the four-phase flow diagram of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement [14]. This report is based on the PRISMA Statement.

2.1. Search strategy and study selection

Studies written in English were identified in three international databases: Medline/PubMed, Scopus, and Web of Science. The last search was carried out in September 2015 with no date restriction. The following search strategy was used: composite* AND repair* AND (bond* OR adhes*) AND dent*. Literature search results were de-duplicated using EndNote X7 software (Thomson Reuters, New York, NY, USA). The titles of all identified studies were screened by two independent reviewers (L.L.V and R.S.O). Abstracts were carefully appraised when the title indicated inclusion. Articles considered eligible for the review (or in case of doubt) were selected for full-text reading. The total number of full-text articles for reading was divided in two halves and screened by two pairs of independent reviewers (L.L.V and R.S.O; A.P.G. and R.R.M.). Discrepancies were resolved by group discussion. References of all included studies were also hand-searched for additional studies.

2.2. Eligibility criteria

In vitro studies that compared the repair bond strength of direct or indirect methacrylate-based resin composites were selected. For inclusion, composites should have been stored for at least one day in water before testing. Although 24 h storage in water may not actually age the composite, there is no consensus in the dental literature as regards the minimum time of water storage required to properly age dental composites. The 24 h storage was set as minimum time in order to exclude studies that did not store at all the composites in water before testing. In addition, the study should have reported the repair bond strength of composites after use of at least one physical and/or chemical surface treatment compared to a control group. As control group, the composite surface could have been left untreated or ground with dental burs, SiC abrasive papers, or similar abrasives. Grinding was considered an adequate control since intraorally the composite surfaces are usually finished with burs before repair. Abrasive papers were included as acceptable grinding treatment because their granulometry resembles the granulometry of diamond burs.

When more than one possible control was reported in the study (e.g. untreated composite and composite ground with burs), grinding was selected as the control group. Application of phosphoric acid in the control surfaces was not a reason for exclusion. The following were reasons for exclusion: articles that evaluated composites not based on methacrylate technology (e.g. silorane or ormocer), absence of composite aging or storage in dry conditions before the repair (including the control group), and use of unusual bond strength test (e.g. transverse strength). When all groups of a given investigation were submitted to a common surface treatment (e.g. all specimens were air-abraded or silanated), this study was also excluded due the absence of an appropriate untreated (or only ground) control group.

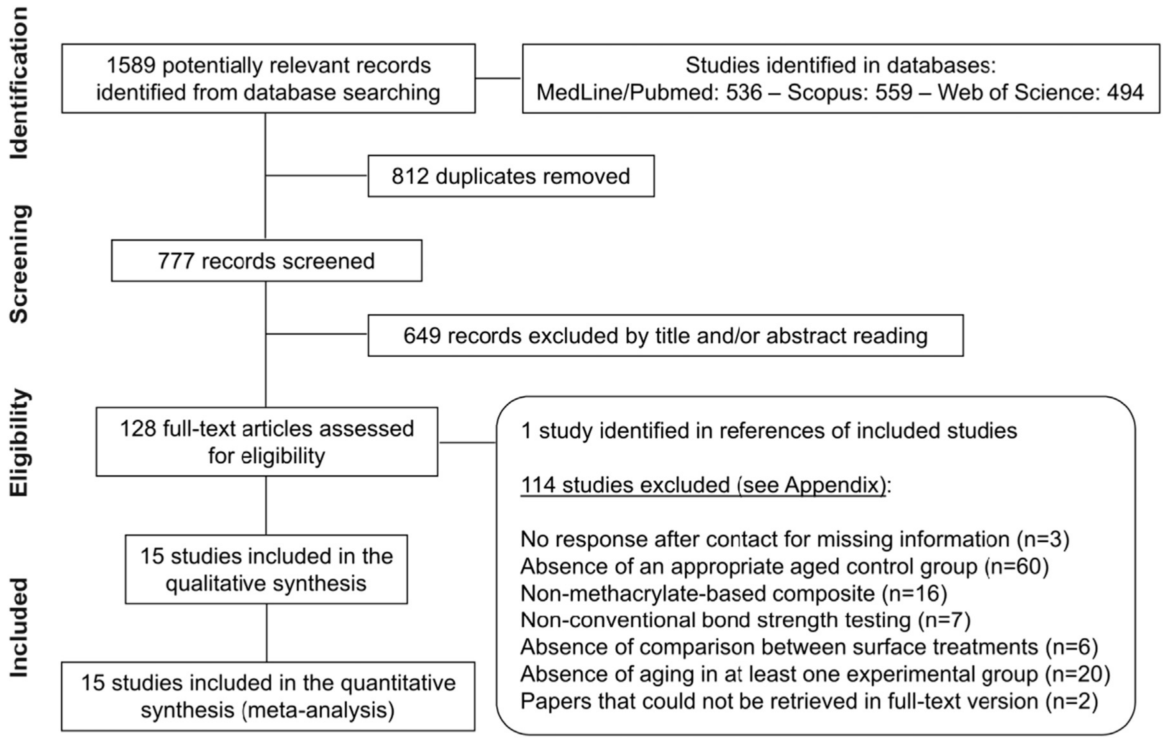


Fig.1. Flowchart of the systematic review.

2.3. Data collection

A standard outline was used for data extraction based on the characteristics of studies and groups tested: composite type (e.g. hybrid, microfilled, nanofilled), aging method and time, bond strength test, and surface treatments tested. The surface treatments were separated in physical treatments (airborne-particle abrasion or hydrofluoric acid-etching), chemical treatments (silane, adhesive, or silane + adhesive), or physical + chemical treatments (combination of physical with one or more chemical treatments). Hydrofluoric acid-etching with was classified a physical treatment because its main effect on composite is the creation of surface roughness. Repair bond strength means, standard deviations, and sample sizes were extracted for all groups of interest.

When the study evaluated more than one composite or more than one storage type, for instance, data were extracted individually for each composite and storage time tested. Cohesive strengths of unrepaired, non-aged composites were also extracted when available. Authors of studies were contacted in case of missing data (e.g. data provided in graphs); these studies were only included if the authors provided the missing information. When the study had more than one group for a same treatment (e.g. three adhesives brands) but only one control group, data for only of the experimental groups were extracted. Selection of only one experimental group was necessary to avoid overestimation of results if several similar treatments were compared against a single control group. When necessary, experimental group selection considered the treatment most commonly used in the clinical setup (e.g. two-step, etch-and-rinse adhesive over a two-step, self-etch adhesive). Data extraction was carried out by consensus among the four researchers conducting the extraction.

2.4. Data analysis

Characteristics of studies were summarized descriptively. When sufficient data were available, a meta-analysis was conducted using random effects model to calculate pooled mean differences between control composite and composite subjected to a given surface treatment. Within each different surface treatment approach (physical, chemical, and physical + chemical), subgroups were created and a separate analysis was carried out considering distinct treatments (e.g. silane, adhesive, and silane + adhesive for chemical methods). Bond strength data extracted were restricted to those from studies in which surface treatments were compared under same conditions and when a pairwise comparison was available. All summary estimates were reported with point estimates and corresponding 95% confidence intervals (CIs). Statistical heterogeneity was assessed using the Cochrane Q statistic and I^2 test ($>75\%$ indicates high heterogeneity) [13]. The analyses were conducted using Review Manager 5.3 software (Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014).

2.5. Assessment of risk of bias

The risk of bias of all included studies was assessed based on The Cochrane Collaboration's tool for assessing risk of bias [15] and previous studies [16,17]. The following parameters were considered: randomization of specimens, materials used according to manufacturers' instructions, sample size calculation, blinding of the operator of the testing machine, and use of storage method able to age the composite before repair. Each item was judged as having high, low, or unclear risk of bias according to the report in each article. The parameters used were discussed by the researchers involved and judgment was carried out by group discussion. Assessment of risk of bias was conducted using Review Manager 5.3 software.

3. Results and discussion

The flowchart of the systematic review is shown in Fig. 1. After screening 777 unique titles and 128 full-text articles, 14 studies

Table 1
Data extracted from the studies included in the systematic review.

Author, Year	Aged composite type (commercial name)	Aging method before repair	Aging time	Bond strength test	Surface treat-ment - Type	Surface treatment - Groups	Bond strength. MPa	SD	*N*
Al Musa and Al Nahedh, 2014 [18]	Hybrid (Aelite LS Posterior)	Water	4 weeks	Shear	Control	None	14.1	4.5	12
						Cohesive strength (non-aged)	14.9	2.3	12
					Chemical	Adhesive	16.2	4.8	12
Bacchi et al., 2013 [19]	Microhybrid (Filtek P60)	Water at 37 °C	6 months	Tensile	Control	Abrasive	5.6	2.3	10
					Chemical	Adhesive	16.7	5.7	10
						Silane + adhesive	16.2	6.0	10
					Physical + chemical	Air abrasion + adhesive	19.4	5.2	10
						Air abrasion + silane + adhesive	18.7	3.6	10
Bouschlicher et al., 1997 [20]	Microfill (Silux Plus)	Water at 37 °C	24 h	Shear	Control	Abrasive	9.9	2.9	10
					Physical	Air abrasion	10.1	2.4	10
					Chemical	Silane	13.6	2.6	10
					Physical + chemical	Air abrasion + silane	10.5	1.8	10
	Hybrid (Pertac Hybrid)	Water at 37 °C	24 h	Shear	Control	Abrasive	9.7	2.8	10
					Physical	Air abrasion	6.6	2.3	10
					Chemical	Silane	10.5	3.1	10
					Physical + chemical	Air abrasion + silane	12.8	4.8	10
Brosh et al., 1997 [21]	Hybrid (Pertac Hybrid)	Water at 37 °C	14 days	Shear	Control	Abrasive	7.9	2.9	20
					Physical	Air abrasion	5.6	3.0	20
						HF acid-etching	5.7	2.2	20
					Chemical	Adhesive	8.0	2.5	20
						Silane + adhesive	9.1	2.5	20
					Physical + chemical	Air abrasion + adhesive	10.6	3.6	20
						Air abrasion + silane + adhesive	9.1	2.8	20
						HF acid-etching + adhesive	6.0	2.3	20
						HF acid-etching + silane + adhesive	6.4	2.2	20
Cavalcanti et al., 2007 [22]	Microhybrid (TPH Spectrum)	Water at 37 °C	24 h	Microtensile	Control	Abrasive	31.4	5.2	10
						Cohesive strength (non-aged)	43.8	7.2	10
					Physical	Air abrasion	33.3	12.5	10
					Chemical	Adhesive	31.7	4.0	10
					Physical + chemical	Air abrasion + adhesive	33.8	7.1	10
Eli et al., 1988 [32]	Hybrid (P30)	Human saliva at 37 °C	48 h	Shear/Tensile	Control	Abrasive	18.1	5.1	20
						Abrasive	21.7	6.4	20
						Cohesive strength (non-aged)	36.4	5.9	20
					Chemical	Adhesive	27.9	6.2	20
						Adhesive	26.0	9.3	20
	Hybrid (Visiofil)	Human saliva at 37 °C	48 h	Shear/Tensile	Control	Abrasive	15.5	4.2	20
						Abrasive	20.0	8.3	20
						Cohesive strength (non-aged)	39.8	0.7	20
					Chemical	Adhesive	28.2	7.4	20
						Adhesive	24.9	7.7	20
Fawzy et al., 2008 [23]	Microhybrid (Gradia Anterior)	Water at 37 °C	30 days	Microtensile	Control	None	2.9	1.1	8
						Cohesive strength (non-aged)	18.8	4.5	8
					Chemical	Adhesive	4.0	1.0	8
						Silane + adhesive	6.7	1.4	8
Hamano et al., 2011 [24]	Microhybrid (Ceram●X Duo)	Boiling water	24 h	Microtensile	Control	Abrasive	29.7	9.3	27
						Cohesive strength (non-aged)	43.4	9.5	26
					Chemical	Silane	27.4	9.9	25
						Adhesive	29.9	14.0	25
						Silane + adhesive	29.4	11.1	28
				Microtensile (after TC)	Control	Abrasive	30.5	8.8	25
					Chemical	Silane	33.2	10.3	25
						Adhesive	30.5	11.6	27
						Silane + adhesive	32.1	9.6	33
Imbery et al., 2014 [25]	Nanofill (Filtek Supreme Ultra)	Water at 37 °C	7 days	Shear	Control	Abrasive	9.4	4.4	12
						Cohesive strength (non-aged)	11.3	3.3	12
					Chemical	Adhesive	17.4	3.5	12
						Silane + adhesive	10.6	8.4	12

Table 1 (*continued*)

Author, Year	Aged composite type (commercial name)	Aging method before repair	Aging time	Bond strength test	Surface treatment - Type	Surface treatment - Groups	Bond strength. MPa	SD	*N*
Jafarzadeh Kashi et al., 2011 [26]	Microhybrid (Clearfil AP-X)	Water at 37 °C	3 weeks	Shear (7 days)	Control	None	3.4	1.6	15
					Chemical	Adhesive	27.3	1.8	15
						Silane + adhesive	59.1	7.9	15
				Shear (6 months)	Control	None	1.0	0.8	15
					Chemical	Adhesive	25.7	1.9	15
						Silane + adhesive	50.8	4.6	15
Kaneko et al., 2015 [27]	Microhybrid (Filtek P60)	Water at 37 °C	10 days	Tensile	Control	Abrasive paper	3.8	0.9	10
						Cohesive strength (non-aged)	60.9	16.7	10
					Chemical	Adhesive	18.0	6.8	10
						Silane + adhesive	15.1	5.3	10
					Physical + chemical	Air abrasion + adhesive	24.2	7.9	10
						Air abrasion + silane + adhesive	28.4	7.0	10
Öztas et al., 2003 [28]	Microhybrid (Charisma)	TC	300 cycles	Shear	Control	Abrasive	11.4	3.2	8
					Physical	Air abrasion	18.2	3.2	8
					Chemical	Adhesive	12.8	5.4	8
					Physical + chemical	Air abrasion + adhesive	23.2	5.2	8
Rathke et al., 2009 [29]	Microhybrid (TPH Spectrum)	Sodium chloride solution at 37 °C	24 h	Tensile	Control	Abrasive	21.3	5.0	10
					Physical	Air abrasion	19.5	2.9	10
					Chemical	Adhesive	22.7	2.6	10
					Physical + chemical	Air abrasion + adhesive	22.4	4.3	10
						Air abrasion + silane + adhesive	26.7	2.0	10
			6 months	Tensile	Control	Abrasive	15.8	4.0	10
					Physical	Air abrasion	16.6	6.1	10
					Chemical	Adhesive	23.3	2.9	10
					Physical + chemical	Air abrasion + adhesive	23.4	3.9	10
						Air abrasion + silane + adhesive	24.6	4.7	10
Shahdad and Kennedy, 1998 [30]	Microfill (Helio Progress)	Water at room temperature	24 h	Shear	Control	Abrasive	22.7	3.8	12
						Abrasive	24.4	3.7	12
						Cohesive strength (non-aged)	28.7	4.8	12
					Chemical	Adhesive	23.9	2.5	12
						Adhesive	27.5	4.2	12
Tezvergil et al., 2003 [31]	Microhybrid (Filtek Z250)	Boiling water + water at 37 °C	8 h + 3 weeks	Shear (water)	Control	Abrasive	17.8	4.6	8
					Chemical	Adhesive	35.7	7.1	8
						Silane + adhesive	44.7	6.1	8
				Shear (after TC)	Control	Abrasive	17.1	2.3	8
					Chemical	Adhesive	33.4	7.2	8
						Silane + adhesive	42.4	8.4	8

TC: thermal cycling; SD: standard deviation.

[18–31] were initially included and one extra study [32] was added from the reference lists, whereas 114 studies (see Appendix) were excluded for reasons reported in Fig. 1. Approximately 70% of the studies excluded did not present what was considered here as appropriate aged control or experimental groups, meaning that comparisons between aged control composites and aged composites subjected to surface treatments before repair were not feasible.

3.1. Overall results

Characteristics of the included studies and extracted data can be seen in Table 1. Most studies (82.4%) tested (micro)hybrid materials as aged composites to be repaired. The repair bond strength test most commonly used was (micro)shear test (60%), followed by (micro)tensile test (33.3%); one study reported the use of a bond strength test combining shear and tensile stresses. Results for the judgment of risk of bias in the studies included are presented in Fig. 2. Whereas randomization of specimens was carried out in the majority of studies, less than 50% of the studies reported that materials were used according to the manufacturers' instructions. Sample size calculation or blinding of the operator of the testing machine were either reported in few studies or not reported at all. Approximately 25% of the studies included in this systematic review employed methods for aging the composites that were considered of high risk of bias, i.e., perhaps not able to age the composites.

3.2. Aging composites before repair

Static storage in water or similar media was the method most often used for aging the composites (82.4%), whereas only 17.6% of the comparisons reported here involved more complex aging methods, such as thermal cycling or boiling in water. In some cases, assessing the effect of storage periods before repair was actually the goal of the authors, and comparisons between storage for 24 h and longer periods were reported. Although there is no aging protocol indisputably considered gold standard for

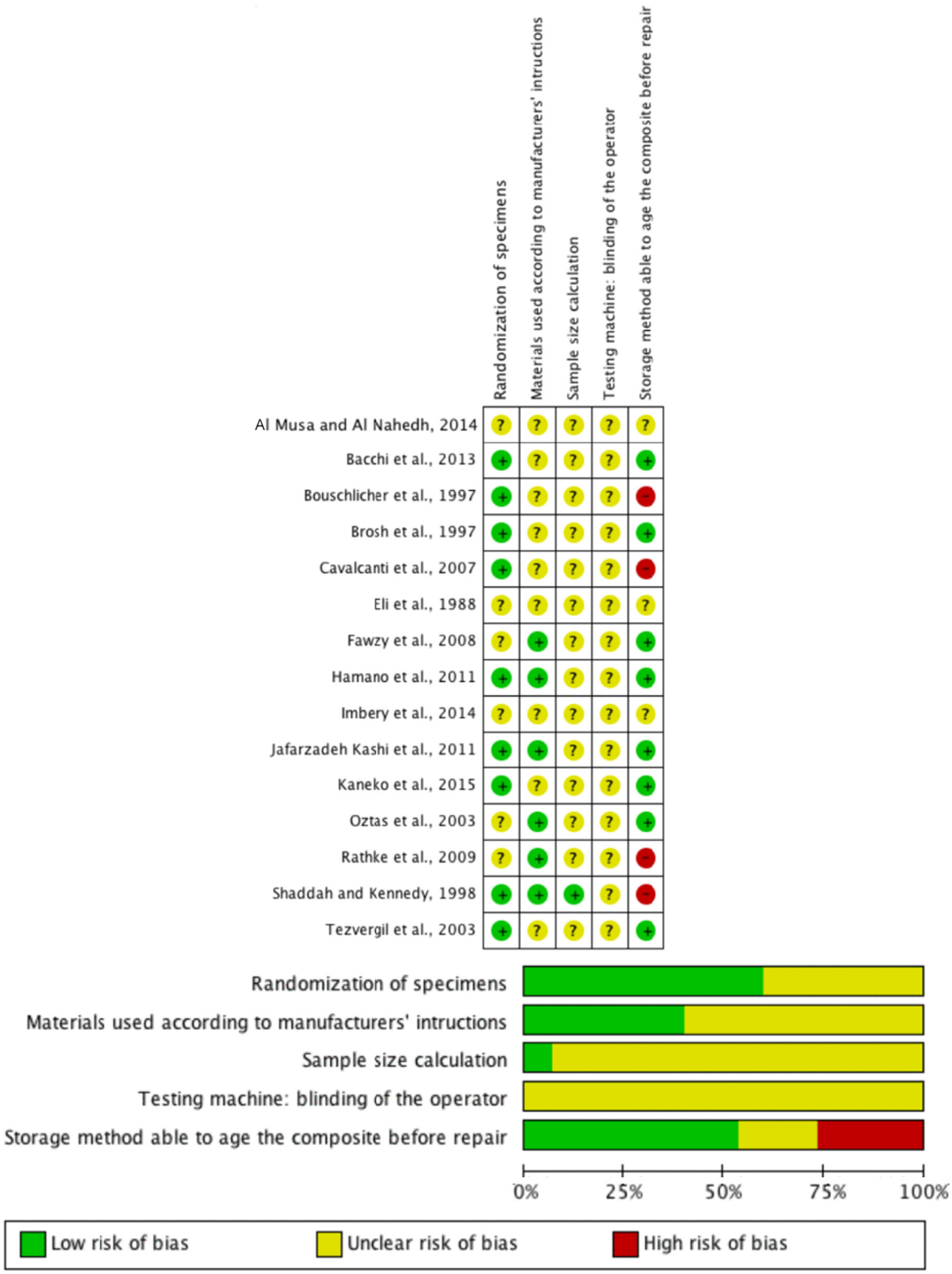


Fig. 2. Risk of bias analysis: authors' judgements on each item for each included study and proportion of studies with low, unclear, or high risk of bias for each item.

mimicking the aging that dental composites are subjected in the oral environment, it seems that many of the aging protocols used in the studies unlikely aged the composites properly. This assumption is reinforced when one analyzes the reported storage times before repair: 44.4% of studies stored the composites for up to 48 h in water, whereas only 22.2% of the studies aged the composites in water for 30 days or longer.

Aging the composites properly before repair is crucial to investigate their repair potential in a setup that resembles the clinical environment. Although composite restorations sometimes show early clinical failures, these failures tend to be related to

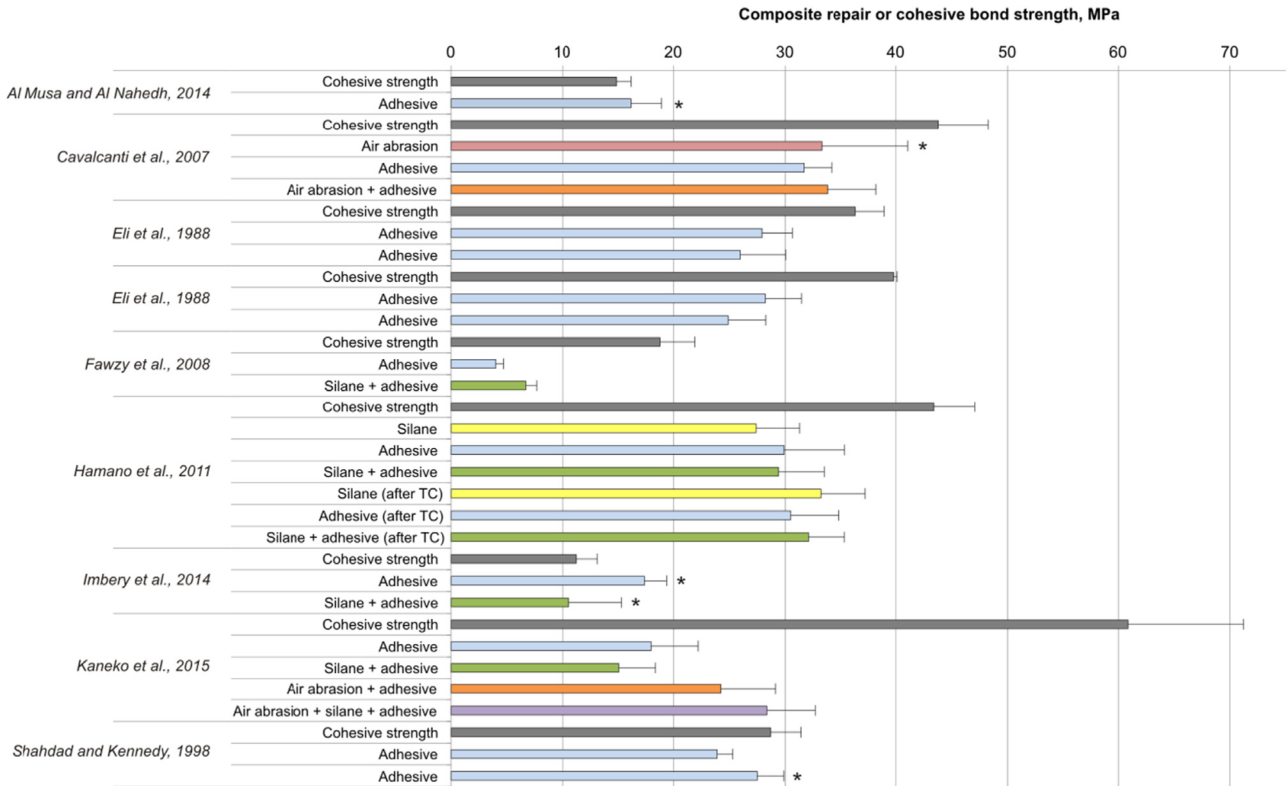


Fig. 3. Graph showing the comparisons between the cohesive strengths (gray bars) and repair bond strengths reported in each study (bars are means +95% confidence intervals). Asterisks indicate groups with repair bond strengths at least similar to the original cohesive strengths. Only studies reporting the cohesive strength of non-aged composites were included (studies were repeated when tested more than one composite). TC: thermal cycling.

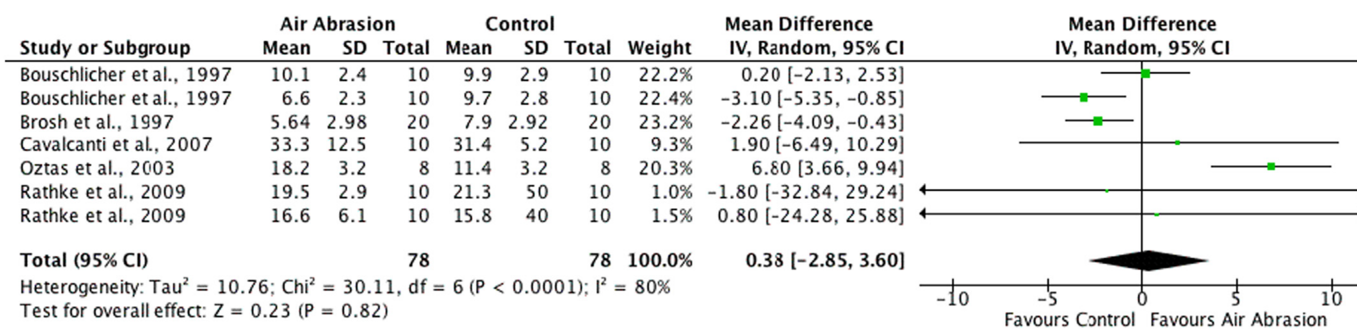
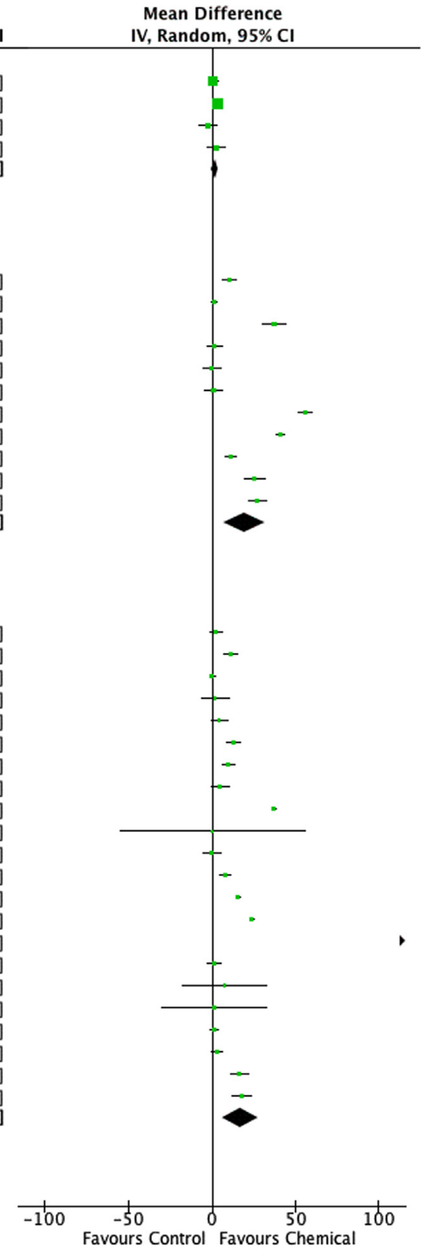


Fig. 4. Summary of findings of the meta-analysis comparing the repair bond strength of control composites and composites subjected to physical surface treatments before repair. Air abrasion was included as only physical treatment as few comparisons were available for other methods (e.g. etching with hydrofluoric acid).

chipping or other minor fractures. In those situations, perhaps patients would not seek for immediate repair. Failures prone to be repaired, in contrast, are expected to happen in the medium or long term clinical service of restorations [3,4], when the composite is "old". Recently-cured composites are more reactive than aged composites due to two main aspects. On one hand, free radicals and more importantly free monomers are still available in recently-cured materials [33], improving their ability to bond to the "new" composite upon repair. On the other hand, it takes time for hygroscopic and hydrolytic effects of water to take place within the 3D, cross-linked polymer structure [34]. Water absorption and polymer swelling are responsible for relaxing the physical bonds between polymer chains [34], allowing free monomers and inactive polymerization promoters to be eluted. With time, hydrolysis of polymer chains and filler-polymer interfaces may also occur [34], contributing to physical and chemical degradation of the restorative. In that scenario, when improper aging of the composite is present, the effect of surface treatments might be over or underestimated *in vitro* due to the potentially good chemical coupling between materials at the bonded interface. However, to date there is no gold standard method for aging dental composites and simulating the quite complex oral conditions.

The cohesive strengths of non-aged composites, usually used as a reference value for the optimal repair bond strength of aged composites, were reported in approximately 53% of the studies. This low frequency of report is another concern. Application of physical and/or mechanical treatments to aged composites is carried out in an endeavor to reestablish the bonding potential of the degraded, low-reactive material. Although a comparison between untreated and treated aged surfaces is interesting to observe whether the applied treatment had a positive effect on the repair potential, the ultimate goal is to reestablish the original composite cohesive strength. Fig. 3 shows a comparison between the cohesive strengths and repair bond strengths reported in each study. It is noteworthy that only in 20.8% of the pairwise comparisons the applied surface treatments were able to yield bond strengths at least similar to the original composite

Study or Subgroup	Chemical Mean	Chemical SD	Chemical Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
1.3.1 Silane								
Bouschlicher et al., 1997	10.5	3.1	10	9.7	2.8	10	34.2%	0.80 [−1.79, 3.39]
Bouschlicher et al., 1997	13.6	2.6	10	9.9	2.9	10	36.2%	3.70 [1.29, 6.11]
Hamano et al., 2011	27.4	9.9	25	29.7	9.3	27	15.0%	−2.30 [−7.53, 2.93]
Hamano et al., 2011	33.2	10.3	25	30.5	8.8	25	14.6%	2.70 [−2.61, 8.01]
Subtotal (95% CI)			**70**			**72**	**100.0%**	**1.66 [−0.68, 4.01]**
Heterogeneity: Tau² = 2.44; Chi² = 5.39, df = 3 (P = 0.15); I² = 44%								
Test for overall effect: Z = 1.39 (P = 0.16)								
1.3.2 Silane + adhesive								
Bacchi et al., 2013	16.15	6.04	10	5.63	2.27	10	9.1%	10.52 [6.52, 14.52]
Brosh et al., 1997	9.14	2.51	20	7.9	2.92	20	9.2%	1.24 [−0.45, 2.93]
Fawzy et al., 2008	40	10	8	2.9	1.1	8	9.0%	37.10 [30.13, 44.07]
Hamano et al., 2011	32.1	9.6	33	30.5	8.8	25	9.1%	1.60 [−3.16, 6.36]
Hamano et al., 2011	29.4	11.1	28	29.7	9.3	27	9.1%	−0.30 [−5.70, 5.10]
Imbery et al., 2014	10.6	8.4	12	9.4	4.4	12	9.1%	1.20 [−4.17, 6.57]
Jafarzadeh Kashi et al., 2011	59.1	7.9	15	3.38	1.6	15	9.1%	55.72 [51.64, 59.80]
Jafarzadeh Kashi et al., 2011	50.8	4.6	15	10	0.76	15	9.2%	40.80 [38.44, 43.16]
Kaneko et al., 2015	15.1	5.27	10	3.84	0.87	10	9.2%	11.26 [7.95, 14.57]
Tezvergil et al., 2003	42.4	8.4	8	17.1	2.3	8	9.0%	25.30 [19.26, 31.34]
Tezvergil et al., 2003	44.7	6.1	8	17.8	4.6	8	9.1%	26.90 [21.61, 32.19]
Subtotal (95% CI)			**167**			**158**	**100.0%**	**19.20 [6.84, 31.56]**
Heterogeneity: Tau² = 431.63; Chi² = 1257.33, df = 10 (P < 0.00001); I² = 99%								
Test for overall effect: Z = 3.04 (P = 0.002)								
1.3.3 Adhesive								
Al Musa and Al Nahedh, 2014	16.2	4.8	12	14.1	4.5	12	4.8%	2.10 [−1.62, 5.82]
Bacchi et al., 2013	16.66	5.7	10	5.63	2.27	10	4.8%	11.03 [7.23, 14.83]
Brosh et al., 1997	7.95	2.45	20	7.9	2.92	20	4.8%	0.05 [−1.62, 1.72]
Cavalcanti et al., 2007	33.3	12.5	10	31.4	5.2	10	4.7%	1.90 [−6.49, 10.29]
Eli et al., 1988	25.97	9.31	20	21.658	6.37	20	4.8%	4.31 [−0.63, 9.26]
Eli et al., 1988	28.224	7.35	20	15.484	4.214	20	4.8%	12.74 [9.03, 16.45]
Eli et al., 1988	27.93	6.174	20	18.13	5.096	20	4.8%	9.80 [6.29, 13.31]
Eli et al., 1988	24.892	7.742	20	19.992	8.33	20	4.8%	4.90 [−0.08, 9.88]
Fawzy et al., 2008	40	1	8	2.9	1.1	8	4.8%	37.10 [36.07, 38.13]
Hamano et al., 2011	29.9	140	25	29.7	9.3	27	2.1%	0.20 [−54.79, 55.19]
Hamano et al., 2011	30.5	11.6	27	30.5	8.8	25	4.7%	0.00 [−5.57, 5.57]
Imbery et al., 2014	17.4	3.5	12	9.4	4.4	12	4.8%	8.00 [4.82, 11.18]
Jafarzadeh Kashi et al., 2011	25.7	1.9	15	10	0.76	15	4.8%	15.70 [14.66, 16.74]
Jafarzadeh Kashi et al., 2011	27.3	1.8	15	3.38	1.6	15	4.8%	23.92 [22.70, 25.14]
Kaneko et al., 2015	180	6.81	10	3.84	0.87	10	4.8%	176.16 [171.90, 180.42]
Oztas et al., 2003	12.8	5.4	8	11.4	3.2	8	4.8%	1.40 [−2.95, 5.75]
Rathke et al., 2009	23.3	2.9	10	15.8	40	10	3.8%	7.50 [−17.36, 32.36]
Rathke et al., 2009	22.7	2.6	10	21.3	50	10	3.4%	1.40 [−29.63, 32.43]
Shaddah and Kennedy, 1998	23.9	2.5	12	22.7	3.8	12	4.8%	1.20 [−1.37, 3.77]
Shaddah and Kennedy, 1998	27.5	4.2	12	24.4	3.7	12	4.8%	3.10 [−0.07, 6.27]
Tezvergil et al., 2003	33.4	7.2	8	17.1	2.3	8	4.8%	16.30 [11.06, 21.54]
Tezvergil et al., 2003	35.7	7.1	8	17.8	4.6	8	4.7%	17.90 [12.04, 23.76]
Subtotal (95% CI)			**312**			**312**	**100.0%**	**16.94 [6.31, 27.58]**
Heterogeneity: Tau² = 612.28; Chi² = 7614.53, df = 21 (P < 0.00001); I² = 100%								
Test for overall effect: Z = 3.12 (P = 0.002)								



Test for subgroup differences: Chi² = 14.45, df = 2 (P = 0.0007), I² = 86.2%

Fig. 5. Summary of findings of the meta-analysis comparing the repair bond strength of control composites and composites subjected to chemical surface treatments before repair.

cohesive strength. This reinforces the fact that aged composites are less reactive than fresh composites when it comes to interfacial composite–composite bonding ability. In addition, 80% of the positive results for surface treatments of aged composites generating similar repair potential to the cohesive strength came from studies that used short-term static storage in water (up to 7 days) as aging method. This means that the composites tested in those studies could be more reactive than it would be expected in the clinical situation of repairing dental restorations.

3.3. *Physical treatments*

Fig. 4 shows the results of the meta-analysis for the physical treatments alone vs. control groups. Few comparisons between hydrofluoric acid-etched composite and control composite were available; thus, comparisons were restricted to air abrasion as physical treatment. The pooled effect indicated no significant differences ($p=0.82$) in repair bond strengths between air abraded and control surfaces, with effect size of 0.38 and 95% CI between -2.9 and 3.6. It should be pointed out that the heterogeneity among studies was high ($I^2=80\%$) in this analysis. In addition, approximately 57% of the comparisons included in this analysis originated from studies that stored the composites in water for only 24 h before repair. This means that the results observed for air abrasion compared to control could be over or underestimated. Since the composites could still be reactive in those studies, air abrasion apparently seems to be able to reach almost original cohesive values. Therefore, care should be taken when analyzing the findings of this specific meta-analysis.

Other important aspects that most of the studies missed were the effects that particle type, air abrasion pressure and application time might have on the air abrasion outcome. Alumina particles

Study or Subgroup	Physical + chemical Mean	SD	Total	Control Mean	SD	Total	Weight	Mean Difference IV, Random, 95% CI
1.2.1 Air abrasion + Adhesive								
Bacchi et al., 2013	19.43	5.17	10	5.63	2.27	10	19.1%	13.80 [10.30, 17.30]
Brosh et al., 1997	10.6	3.57	20	7.9	2.92	20	19.8%	2.70 [0.68, 4.72]
Cavalcanti et al., 2007	33.3	12.5	10	31.4	5.2	10	15.3%	1.90 [−6.49, 10.29]
Kaneko et al., 2015	24.23	7.93	10	3.84	0.87	10	18.2%	20.39 [15.45, 25.33]
Oztas et al., 2003	23.2	5.2	8	11.4	3.2	8	18.7%	11.80 [7.57, 16.03]
Rathke et al., 2009	22.4	4.3	10	21.3	50	10	3.7%	1.10 [−30.00, 32.20]
Rathke et al., 2009	23.4	3.9	10	15.8	40	10	5.2%	7.60 [−17.31, 32.51]
Subtotal (95% CI)			**78**			**78**	**100.0%**	**9.81 [3.20, 16.43]**
Heterogeneity: $Tau^2 = 56.37$; $Chi^2 = 66.06$, df = 6 (P < 0.00001); $I^2 = 91\%$								
Test for overall effect: Z = 2.91 (P = 0.004)								
1.2.2 Air abrasion + Silane + Adhesive								
Bacchi et al., 2013	18.73	3.64	10	5.63	2.27	10	27.1%	13.10 [10.44, 15.76]
Brosh et al., 1997	9.06	2.8	20	7.9	2.92	20	27.3%	1.16 [−0.61, 2.93]
Kaneko et al., 2015	28.36	6.98	10	3.84	0.87	10	26.4%	24.52 [20.16, 28.88]
Rathke et al., 2009	24.6	4.7	10	15.8	40	10	11.4%	8.80 [−16.16, 33.76]
Rathke et al., 2009	26.7	20	10	21.3	50	10	7.8%	5.40 [−27.98, 38.78]
Subtotal (95% CI)			**60**			**60**	**100.0%**	**11.76 [0.78, 22.75]**
Heterogeneity: $Tau^2 = 114.02$; $Chi^2 = 123.93$, df = 4 (P < 0.00001); $I^2 = 97\%$								
Test for overall effect: Z = 2.10 (P = 0.04)								
Test for subgroup differences: $Chi^2 = 0.09$, df = 1 (P = 0.77), $I^2 = 0\%$								

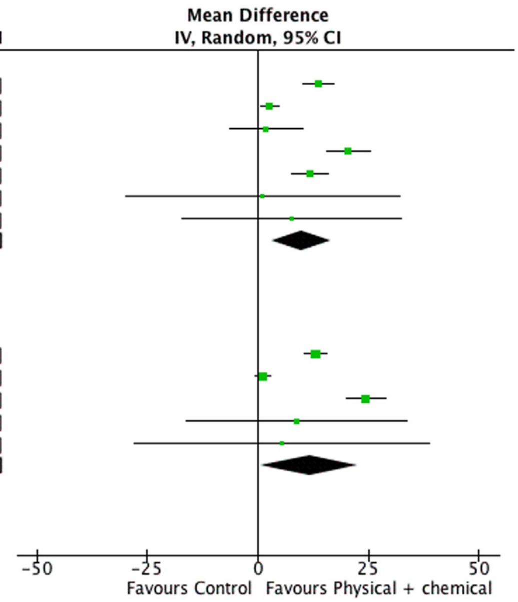


Fig. 6. Summary of findings of the meta-analysis comparing the repair bond strength of control composites and composites subjected to physical + chemical surface treatments before repair.

(usually 50 μm in size) were used 71.4% of the comparisons included in this analysis, with no report on the effect of abrasion pressure or time. Air abrasion is able to generate surface roughening on the aged composite by mechanical shocking of alumina particles, non-selectively removing portions of the polymer matrix and filler particles. Subsequently, mechanical retention occurs by interpenetration of the aged and fresh to form a bonded interphase. When silica-coated alumina particles are used in air abrasion, in addition to micromechanical retention, air abrasion is able to leave a silica-reach layer at the composite, which could additionally contribute to chemical coupling at the interface via subsequent silanization. Finally, the similar repair bond strengths between control and air-abraded surfaces could be explained by the formation of cracks at the surface and subsurface of composites subjected to air abrasion [35]. However, the formation of cracks occur mainly in brittle materials, which might present reduced mechanical strength after air abrasion. Nonetheless, it is usually expected that air abraded surfaces (or surfaces treated by other physical means) should be subsequently treated with a chemical coupling agent for improved repair potential.

3.4. *Chemical treatments*

Fig. 5 shows the results for the meta-analysis comparing chemical treatments of the composite and control groups. No significant effect was observed for silane applied alone (effect size: 1.7; 95% CI: −0.7, 4.0; $I^2=44\%$). This result can be explained by the fact that although silanes are able to improve the wetting of resin-based materials at the restorative surface, their chemical coupling with the composite depends upon the availability of silica at the surface (i.e., glass particles). In the conditions tested in the included studies, the silica content at the aged composite was probably not high since no physical treatment was applied before repair; thus, most glass filler particles are still coated by the polymer matrix and not prone to form siloxane bonds. The degradation of dental composites upon storage is also able to break filler-polymer bonds [34], allowing surface loss of glass particles. However, it should be highlighted that the number of studies included in the analysis was low.

In contrast, the analysis favored both application of adhesive alone (effect size: 16.9; 95% CI: 6.3, 27.6) and silane + adhesive (effect size: 19.2; 95% CI: 6.8, 31.6) as compared to the control ($p=0.002$; $I^2 \geq 99\%$). Considering the results for silane alone, it seems that the presence of an adhesive layer is the major variable playing a role in improving the repair potential of aged composites. The presence of an intermediate, low-viscosity layer of bonding agent improves the chemical bonds between the old and fresh materials, contributing to higher repair bond strengths. In addition, a recent study [36] showed that composites surfaces aged *in vitro* show superficial dissolution and increased surface roughness, which may contribute to mechanical entanglement of the adhesive, whereas the fresh composite is likely too viscous to infiltrate there irregularities. These results may be considered valuable for clinicians, since application of adhesive alone is simpler than combining silane + adhesive. In addition, it is already expected that clinicians will apply an adhesive system to all cavity preparation (including aged composite and dental structure) before repairs. However, it should be bore in mind that the effect of silane might be dependent on the type of composite involved in the repair, i.e. the positive effect of silane for composites different from those tested in the studies included here should not be ruled out. Also, most of current dental adhesive systems rely on the presence of MDP and other acidic methacrylate monomers that potentially may improve the composite repair bond strengths. Unfortunately, the data gathered in this systematic review was not sufficient to establish any comparison between MPD-containing adhesives vs. adhesives without MDP.

3.5. *Physical + chemical treatments*

The meta-analysis comparing the combination of physical and chemical treatments of the composites and control groups is shown in Fig. 6. As mentioned for the physical treatments alone, comparisons here were restricted to air abrasion as physical treatment because only a few comparisons for hydrofluoric acid-etching + a chemical treatment were available. In addition, combination of air abrasion was only possible with two chemical treatments: adhesive, and silane + adhesive. The analysis favored the combination of air abrasion with both adhesive (effect size: 9.8; 95% CI: 3.2, 16.4;

$p=0.004$; $I^2=91\%$) and silane + adhesive (effect size: 11.8; 95% CI: 0.8, 22.8; $p=0.04$; $I^2=97$). In contrast to the application of chemical agents alone, it seems that both silane coupling agents and adhesives play a role in improving the repair bond strengths when physical treatments are applied to the aged composite. These results are in line with a recent study [16] showing that physical treatment of glass-fiber posts, for instance, are necessary for proper action of silanes. The physical treatment is able to dissolve or remove the polymer matrix covering the glass fibers or particles, creating a proper scenario for silane coupling agents to interact with silica. For the adhesive agent, the increased surface roughness contributes to mechanical keying, improving the repair bond strengths.

3.6. Final remarks

Results of this systematic review provide evidence that chemical or physical + chemical treatments of aged composite surfaces may contribute to improve their repair bond strengths. High heterogeneity was observed in most statistical analyses carried out here; factors and variables contributing to this high heterogeneity are hard to identify considering that the studies included in the review have a high number of covariates involved. Potential problems associated with reporting were also indicated by the analysis of risk of bias; unfortunately, reporting problems are common in the *in vitro* literature. In addition, the present results may have been influenced by publication bias, as studies with negative results could not have been published. Therefore, it is suggested that *in vitro* studies on the repair bond strength of dental composites should include:

- Use of storage methods that could properly age dental composites, preferably including prolonged water storage at 37 °C (to simulate hydrolytic degradation) combined with mechanical or cyclic loading (to simulate mechanical degradation);
- A control group defined by no surface treatment of the aged composite, or alternatively treating the aged control surfaces only with abrasives (burs or SiC papers);
- A reference group testing the cohesive strength of non-aged composites;
- Use of restorative and bonding materials according to the manufacturer's instructions (or indicating why directions were altered), blinding the operator of the testing machine, estimation of sample size, and randomization of specimens, in order to reduce risk of bias associated with the methodology;
- Proper report of all variables that might interfere with the repair bond strength outcomes.

4. Conclusion

Application of chemical or physical + chemical surface treatments of aged dental composites seems beneficial for improving the repair bond strength of methacrylate-based restoratives. Silane coupling agents appear to have a minor role as compared to adhesive agents in improving the repair potential after composite roughening. Airborne-particle abrasion alone was found not to improve significantly to the repair bond strengths, but this result should be analyzed with caution since a great part originated from comparisons where the "old" composite was aged using short-term static water storage.

Appendix

Studies excluded from the systematic review (reasons reported in Fig. 1):

[37–150].

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