



## A Systematic Review of Amalgam Bonded Restorations: *In vitro* and Clinical Findings

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### ABSTRACT

**Aim:** This article aims to systematically review the evidence reporting on physical properties of bonded amalgam, its clinical performance, and implications.

**Materials and methods:** An electronic search in “Medline” (search term: Amalgam and Dentin bonding) from 1987 to 2013 yielded 465 publications out of which 170 articles were selected for the analysis. Data were extracted relating to the bond strength of amalgam to dentin, microleakage, postoperative sensitivity, and longevity of bonded amalgam restorations.

**Results:** A total of 129 *in vitro* studies out of 170 articles showed high bond strengths with filled adhesive resins and light-cured adhesives, in particular Amalgambond plus and Optibond adhesives. Thickness of bonding agent, type of alloy, and thermocycling showed inconclusive outcomes between bonded and nonbonded amalgam restorations. Majority of studies reported reduced microleakage when dentin bonding agents and resin-modified glass ionomer cements (RM-GICs) were used with amalgam. However, water stored, thermocycled, and spherical amalgam alloys resulted in higher microleakage. While bonded amalgam facilitated the retention of large restorations, reduction in postoperative sensitivity was not consistently observed between bonded and nonbonded amalgam restorations.

**Conclusion:** While bonded amalgam restorations reduce the need for mechanical retention conserving tooth structure and reducing the adverse effects of microleakage, there is lack of consistent evidence across all outcome domains to advocate the benefit of bonding of all amalgam restorations. Despite this, it can be considered the material of choice for large restorations and bonding enhances retention *in vitro* which can be considered beneficial clinically.

**Clinical significance:** The use of adhesives to bond amalgam to the tooth structure offers potential advantages, as it helps in conservative cavity preparation without compromising the retention to tooth, making it a material of choice in large posterior restorations.

**Keywords:** Adhesives, Bond strength, Bonded amalgam, Longevity, Microleakage, Sensitivity, Systematic review.

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### INTRODUCTION

Dental amalgam has been a ubiquitous restorative material that has been used successfully for centuries to restore small and large cavities. Despite the use of composite restorative materials with advanced esthetics, amalgam is still considered as the restoration of choice for complex molar preparations due to its longevity, ease of use, and low cost. Recent literature has reported that amalgam restorations have an average lifespan of 15 years compared with composite resins which have a longevity of over 10 years and have annual failure rates of 0.16 to 2.83% compared with 0.94 to 9.43% for composites at 7 years.<sup>1</sup> This is regardless of the tooth type and the number and dimensions of surfaces restored.<sup>2</sup> In addition, the use of amalgam cores for crowns have a greater survival in terms of fracture resistance and durability compared with the resin and glass ionomer restorations.<sup>3</sup>

However, while providing functional surfaces, it has limitations in restoring the strength of the tooth, is susceptible to secondary caries, is unesthetic and poses environmental concerns.<sup>4,5</sup> In an attempt to improve the longevity and function of amalgam restorations,

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bonding agents have been used with the aim of improving retention, and reducing microleakage and secondary caries.

*In vitro* studies have demonstrated added retention and a reduction of microleakage with bonded amalgam, which suggests the potential for better clinical outcomes.<sup>6</sup> Clinical studies, however, have shown variable results<sup>7-9</sup> and a recent systematic review has questioned the benefit of bonding amalgam.<sup>10</sup> Also, while a number of countries have banned amalgam<sup>11,12</sup> or are in the process of doing so,<sup>13</sup> there are many regions of the world that are unlikely to be able to do this due to resource or financial concerns. This suggests that amalgam restorations will still be placed for many years to come.<sup>13,14</sup> There is a need to examine the literature on bonding amalgam with regard to *in vitro* and clinical data to inform practice despite its dwindling use.

The aim of this study is to perform a qualitative systematic review to evaluate both *in vitro* and *in vivo* evidence for bonding amalgam restorations.

## MATERIALS AND METHODS

The aim of this review was to search the literature to identify the use of bonded amalgam, its clinical performance, and implications. The PubMed database was used to search for literature related to amalgam bonded to dentin. These included review papers, *in vitro* and *in vivo* studies from 1987 to 2013.

The inclusion criteria used were: Amalgam bonded to dentin; or bond strength of bonded amalgam; or microleakage of bonded amalgam restorations; or fracture resistance of bonded amalgam; or postoperative sensitivity after placement of bonded amalgam.

The exclusion criterion used was: Articles published in a language other than English.

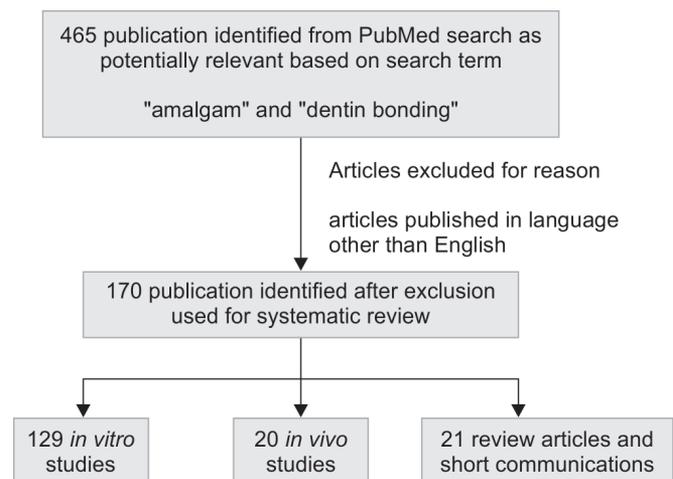
The search keywords for PubMed were: ("Amalgam" AND "Dentin bonding").

After the PubMed search, 465 articles were initially found. After reading the titles and abstracts of the articles, 170 articles were selected, including 129 *in vitro* studies, 20 *in vivo* studies, and 21 review articles or short communications on the longevity and physical properties of amalgam restorations (Flow Chart 1).

## RESULTS

The majority of the articles were *in vitro* studies. More than half of the articles were on bond strength of amalgam to dentin bonded with different adhesives. The remaining *in vitro* articles were related to microleakage, fracture resistance, and scanning electron microscope (SEM) studies, while *in vivo* studies focused on postoperative sensitivity and longevity.

**Flow Chart 1:** Selection process of articles included for the systematic review



### *In vitro* Studies

#### Shear Bond Strength

Thirty studies were found that examined the shear bond strength of amalgam to tooth tissue (enamel and dentin). The vast majority of these used resin cements, while a few used RM-GICs. One of the papers was excluded due to duplicate results in two of the papers by the same author.<sup>15,16</sup> This resulted in 29 studies in total.

#### Resin Cement

The *in vitro* data of shear bond strength testing between amalgam and dentin showed a range of 3.89 to 37.4 MPa, using a range of testing protocols including the shear bond strength test and tooth model.

Prior to the 1990s, Shimizu et al<sup>17</sup> reported a shear bond strength of 4.0 to 4.5 MPa for Panavia and Superbond. In the early 1990s, Amalgambond appeared to be the main resin cement investigated, and a wide range of strength values (0.89–5.1 MPa) were reported. Since 1994, with the availability of Amalgambond Plus with high performance additive (HPA) and All-Bond 2, bond strength values appeared to increase (6.23–14.57 MPa). From 2000 onward, there was a wider range of resin cements available; however, the shear bond strength did not seem to show an observable increase (2.0–9.91 MPa).

It is realized that the large variation of values reported for the same products was due to the different design protocols implemented by different authors, including different cements, methodology, storage time, and thermocycling duration. Five of the 29 papers reported Amalgambond Plus with HPA to have some of the highest bond strengths.<sup>18-20</sup> In addition, OptiBond was reported to have the highest or second highest (to Amalgambond Plus with HPA) bond strength to dentin.<sup>20-22</sup>

Out of all the resin cements bonded to dentin tested by different studies, Amalgambond Plus with HPA and OptiBond generally gave the highest or second highest bond strengths.

### Thermocycling

Thermocycling has become a common feature of dental materials' bond strength testing as the luting agent and the bonding interfaces can all be affected by the thermal changes occurring after its setting time. Thermocycling can produce adverse physical effects on the bonded assembly due to different coefficients of thermal expansion between the tooth, the cement, and the bonded dental material. These thermal stresses can lead to microstructural changes resulting in alterations in the physical properties of the set resin cements. Thermocycling is often used when testing the durability of luting agents to tooth tissue.

The comparative effects of thermocycling to no thermocycling have only been shown in one study by Chang et al.<sup>23</sup> One group of specimens was stored in 37°C distilled water for 24 hours, while the other was thermocycled between 5°C and 55°C for 1,000 cycles. The thermocycled and nonthermocycled specimens exhibited bond strengths of 9.07 and 10.02 kg/cm<sup>2</sup> respectively, a significant reduction of 9.5%. The authors concluded that thermocycling adversely affects the shear bond strength of amalgam to dentin. While twelve other studies reported thermocycling, these did not incorporate a control of specimens not subjected to thermocycling.

One study showed thermocycling to adversely affect the shear bond strength of amalgam to dentin by 9.5%.

### Storage Time

Storage time in water is another common test condition for examining the durability of amalgam and dentin bonding, and evaluates the stability of the hybrid layer and the degree to which the bond will undergo hydrolysis over a period of time.<sup>24</sup>

Amalgam dentin bonded specimens are usually stored for a certain period of time before they are tested in a universal testing machine. The majority of shear bond strength studies have examined storage periods of 24 hours and 1 week,<sup>25</sup> while other studies have assessed longer durations of more than 2 months.<sup>15,26</sup>

Only two of the studies compared the effect of different storage time. In a study by Imbery et al,<sup>16</sup> water storage of either 3 or 6 months did not significantly affect the resistance of the specimens tested. This was also supported by Hasegawa et al<sup>25</sup> who demonstrated that shear bond strengths were not adversely affected by the duration of storage in saline for up to 48 weeks. While

limited, these studies seem to suggest that the amalgam bond to resin cement-treated dentin appears relatively stable *in vitro* without thermocycling.

Storage time had no significant effect on the bond strength.

### Thickness of Cement

The thickness of different bonding agents and its influence on the bond strength have been mentioned in some of the studies, although this was not one of the original primary outcomes. Difference in film thickness was observed during SEM studies after shear bond strength testing and then extrapolated to their bond strength.

Grobler et al<sup>18</sup> investigated the bonding of amalgam to dentin with four different cements and concluded from SEM images that resin–dentin hybrid layers of different thicknesses did not have any significant effect on the bond strengths. In contrast, other studies have demonstrated higher bond strengths with greater film thickness,<sup>19,20,22</sup> this possibly being explained by the production of a resin–amalgam interdiffusion layer which facilitates micromechanical locking, thereby enhancing bonding. This is supported by Pashley et al,<sup>27</sup> who considered the infiltration of adhesive resin into demineralized dentin from caries or acid etching important to produce long-term stable bonds compared with those that only partially infiltrate the demineralized zone for amalgam or composite bonding.

Studies on cement thickness were controversial, some found to have no effect while others found that greater cement film thickness produced higher bond strength.

### Volume of Adhesive

The amount of bonding agent used to obtain the best bond strength from the adhesive has been a concern. It is often thought that the tooth should be flooded with adhesives to provide optimal dentin bonding and micromechanical retention with amalgam. Excessive resin cement, however, can also make the carving of the amalgam more difficult and result in an excess of resin extending down the root surface. Therefore, studies have also examined differences in bonding provided by sufficient wetting or excessive wetting of the dentin surface.

Overton and Vance<sup>28</sup> reported no effect of increasing the volume of adhesive applied to the tooth surface on bond strength as long as the surface of the prepared tooth is completely wet with Amalgambond Plus with HPA. Likewise, Barkmeier et al<sup>29</sup> found that an increased number of applications of Amalgambond Plus did not increase bond strength.

Increasing the volume of adhesive had no significant effect on the bond strength.

### Condensation Technique

Proper amalgam condensation results in optimal physical properties and mechanical condensation have been used with the benefits of consistent and efficient condensing force. In an attempt to compare the effect of mechanical and hand condensation, Ratananakin et al<sup>20</sup> found that there was no statistical difference in the shear bond strength of amalgam bonded to dentin, although the thickness of the resulting cement was not measured.

There were no significant effects of condensation technique on bond strength, but based on only one study.

### Filled vs Unfilled

The addition of filler particles to the adhesive resin of newer generation dentin bonding agents available after the mid-1990s resulted in a notable increase in amalgam to dentin bond strengths.<sup>30-32</sup> It was reported by Li et al<sup>33</sup> and Braem et al<sup>34</sup> that the physical properties of resin composite increase with an increase in filler content.

It has been demonstrated by several studies that an increase in filler particles results in higher shear bond strengths due to a thicker and more viscous adhesive layer.<sup>19,20,22,30,35</sup> In an update to Amalgambond Plus, a HPA powder was added, which was claimed to slow polymerization, allowing more time for the monomers to penetrate a dry dentinal surface as well as increasing the physical properties of the bonding agent. Grobler et al<sup>18</sup> mentioned that HPA methacrylate fibers increase the density of the mixture of Amalgambond Plus and form greater entrapment between the filler and amalgam particles, which more than doubled the bond strength from 2.6 to 7.2 MPa.

Filled cements produce better shear bond strength than unfilled cements.

### Light Cure vs Chemical Cure

Resin cements can be activated by chemical activation (self-cured), photo-activated, or dual-cured cements. Chemically activated materials uniformly set even at the bottom of deep cavities, where access for curing light is limited. Photo-activated materials and their set-on-command capability can have a longer working time. de Menezes et al<sup>36</sup> showed that the autopolymerizing system and one of the dual-polymerizing systems were as effective as the light-activated systems in bonding indirect composite restorations to dentin. To examine the effect of different activation modes, studies examine different types of bonding agents with different setting reactions together.

Several studies showed similar or higher bond strengths when adhesives were light-cured prior to amalgam placement compared with chemical cured.<sup>32</sup>

This was also supported by the results of Cianconi et al,<sup>37</sup> who reported that light curing produced better shear bond strength than chemical curing, especially when a spherical alloy was used. In addition, they found that the adhesive interfaces of light-cured material were relatively thick (Prime and Bond NT DC, 6–7  $\mu\text{m}$ ), while the chemically cured adhesives were “relatively thin” (2–4  $\mu\text{m}$ ). Ruyter<sup>38</sup> mentioned that light curing initiates the setting reaction and allows the bottom layer of resin to bond to dentin while the surface layer remains unpolymerized due to the air inhibition layer. When amalgam is condensed against an air-inhibited layer, oxygen is eliminated which allows resin to polymerize more completely and bond mechanically to amalgam.<sup>21</sup> Other studies state that Amalgambond must be wet and of sufficient thickness to be incorporated into amalgam, where amalgam is condensed into unset cement.<sup>15</sup>

Light-cured adhesives result in higher shear bond strength compared with chemical curing.

### Spherical and Admixed Alloy

Some studies have investigated whether amalgam bonding is influenced by the type of amalgam used. Spherical amalgam has high plasticity and a more fluid mix, allowing it to be condensed more easily with lighter force. Spherical amalgam also has lower mercury content, as it requires less mercury to wet the particles and it sets faster than lathe-cut amalgam. Lower mercury content results in less mercury-containing reaction products ( $\gamma_2$  phase) which are softer and weaker. Admixed amalgam (Dispersalloy) is a mixture of lathe-cut and spherical alloys. These factors might affect the handling and performance of the amalgam.

The difference in bond strength associated with the two types of amalgam alloys has been controversial, although available evidence suggests a trend toward higher bond strengths with the spherical alloy. The hypothesis proposed to support the high performance of spherical alloy was that admixed alloy has a slower setting time which was hampered by the removal of mold used during condensation which disturbed the final set and created stress which weakened the bond. Spherical amalgam particles have a larger surface area, increasing the contact area with adhesive. Cianconi et al<sup>37</sup> showed that admixed alloy exhibited both lower bond strengths and less residual amalgam on the debonded dentin surface, meaning that adhesive failure occurs between the adhesive and amalgam, resulting in an adhesive failure. Morrill et al<sup>39</sup> found that spherical alloy had significantly higher SBS to both composite and dentin than did admixed alloy when bonded with Amalgambond. However, Cooley et al<sup>40</sup> found no differences between

spherical and admixed alloy when bonded with Amalgambond.

Some studies showed that spherical alloy produced higher bond strength than admixed amalgam alloy while another study showed no difference when bonded with Amalgambond.

### Resin-modified Glass Ionomer Cement

The majority of the studies investigating amalgam bonding have mainly compared resin cements rather than RM-GICs or GIC. Only three studies on RM-GIC were retrieved in the literature search, which is perhaps a reflection of the greater popularity of resin cements.<sup>41-43</sup> One study reported better bond strength with light-cured RM-GIC (Vitrebond) compared with Amalgambond or Panavia EX.<sup>41</sup> On the contrary, Belcher and Kunsemiller<sup>42</sup> reported higher bond strengths with Amalgambond compared with RM-GIC. In the third study, Dhanasomboon et al<sup>43</sup> reported that application of two layers of resin bonding agents and/or RM-GICs with light polymerization in between resulted in significantly higher shear bond strength than single applications than single coats.

Two out of three studies showed that RM-GIC produced higher bond strength, while one study showed a high bond strength with Amalgambond.

### Tensile Bond Strength

Like shear bond strength testing, tensile bond strength testing shows a similar variance of test materials and methodologies and with a diverse range of results that also makes comparisons between studies unmeaningful. Four studies were identified.

While Miller et al<sup>44</sup> found that amalgam allowed to set for 1, 6, or 24 hours prior to adhesion with Amalgambond to dentin had a higher bond strength than freshly condensed amalgam, however, one must question the clinical relevance of this finding, as it is not clinically practicable. In contrast, Garcia-Barbero et al<sup>45</sup> reported high tensile bond strength with freshly triturated amalgam and cured resin when compared with composite and set amalgam. They also reported that the thickness of adhesive resin should be minimal, as a thicker resin layer may be the cause cohesive failure of amalgam restorations.

In a comparison of dentin pretreatment *vs* no pretreatment when using dentin conditioners prior to All-Bond,<sup>46</sup> no significant difference was observed in the tensile bond strength.<sup>46</sup> Muniz et al<sup>47</sup> evaluated three different adhesive systems and different setting modes for amalgam to dentin. They reported the "highest" tensile bond strengths was observed when Optibond dual-cure adhesive system was light-cured.

The *in vitro* tensile bond strength data showed diverse outcomes. Use of conditioners or light curing of resins was not harmful to strength results.

### Glass ionomer and Amalgam Bonding

Based on an *in vitro* study by Chen et al,<sup>41</sup> bond strengths produced by Fuji-II glass ionomer to amalgam were equivalent to those of Amalgambond Plus and Panavia-21. This study also tested the fracture strength obtained with the application of these three agents onto molar mesial, occlusal, and distal (MOD) cavities, and no statistical differences were found when compared with intact teeth. This suggests that a GIC adhesive liner may improve the strength of MOD amalgam-restored teeth.

In one study, GIC has shown similar bond strength to amalgam resin cements and can improve the strength of teeth *in vitro*.

### Microleakage

The interfacial gap between amalgam and adjacent tooth structure has been reported to be 2 to 12  $\mu\text{m}$ .<sup>48</sup> Factors which may contribute to gap formation and microleakage include: Lack of chemical adhesion, dimensional changes on setting of the amalgam, different thermal coefficients of expansion, inadequate trituration, and poor cavity wall adaptation. This gap between amalgam and dental structure causes problems<sup>49</sup> of penetration of bacteria, "food residue," and salivary components which may cause postoperative sensitivity, discoloration of the tooth, marginal deterioration, secondary caries, and possible pulpal irritation.<sup>50</sup>

Freshly placed amalgam is said to undergo active corrosion at the interface between the tooth and the restoration over time from microleakage of electrolytes along the interfacial gap. Corrosion products, especially tin products ( $\text{SnO}_2$ ,  $\text{SnCl}_2$ , and  $\text{Sn}(\text{OH})_2\text{Cl}$ ) and smaller amounts of calcium and phosphorus,<sup>51</sup> will build up over time and gradually seal the interface.<sup>52,53</sup> Corrosion products have also been shown to reduce microleakage.<sup>49</sup> The lack of "self-sealing" ability in high copper alloys due to low levels of corrosion-susceptible gamma 2 phase, however, may result in substantial microleakage for up to 18 months *in vitro*.<sup>54</sup>

Development of dentin bonding agents has led to the use of adhesive agents to bond amalgam restorations to minimize amalgam microleakage as well as to gain additional retention and protect the dentin/pulp complex.<sup>55</sup>

### Pattern of Microleakage

Dye leakage has been found to be greater at the cementum/dentin margins than enamel.<sup>6,56</sup> This is due to the difference in mineral composition between the two

substrates. Dentin has a higher organic compound composition and is also a moist tissue, resulting in more unstable bonds between the tooth and the adhesive.<sup>57</sup>

Turner et al<sup>58</sup> found that microleakage mainly occurs at the amalgam/resin liner interface rather than the resin/dentin interface, supporting the results of previous studies.<sup>40,55,59</sup> Tangsgoolwatana et al,<sup>60</sup> however, found that greater leakage appeared to occur between the liner and the tooth than between the liner and the amalgam, and suggested that the collapsed collagen on the dentin surface layer may prevent the full depth penetration of dentin bonding agent.

Toledano et al<sup>61</sup> reported SEM evaluations of class V bonded amalgam restorations after thermocycling, and observed the presence of voids along the axial wall. Two of the agents they tested, OptiBond and AElitebond, experienced microleakage between the enamel and adhesive system and/or between the amalgam and the adhesive, but this was not evident with Panavia.

Sano et al<sup>62</sup> defined the term “nanoleakage,” where diffusion of small ions and molecules occurs throughout the dentin hybrid layer in the absence of gap formations. Their study found that with the absence of gap formation, silver nitrate could migrate along the porous zone at the base of the hybrid layer. This type of penetration is probably related to the small size of the silver ion allowing penetration.

However, Gale and Darvell<sup>63</sup> have questioned the microleakage models as since dentin is permeable, it is a confounding factor in tracer penetration tests due to inter- and intratubule connections. Therefore, test results will be affected by the entry of tracer independent of the presence of any marginal gaps, giving false-positive results.

The amalgam–resin interface can be penetrated by dye easier than resin–tooth interface.

### *Effects on Microleakage*

Many studies show that adhesive resin can effectively reduce leakage around amalgam restorations<sup>17,64–69</sup> and found that resin bonding to dentin did not significantly reduce leakage when compared with dentin alone.<sup>67</sup> However, Silva e Souza Junior et al<sup>70</sup> found no difference in microleakage between bonded and nonbonded amalgam restorations.

Although some studies found no effect, most studies showed that bonded amalgam with resin cements reduced microleakage around amalgam restorations.

### *Thermocycling*

Helvatjoglou-Antoniades et al<sup>71</sup> have shown that after thermocycling, there was a significant increase in microleakage when compared with the nonthermocycled

group. They explained that this was due to the difference in the coefficient of thermal expansion between enamel (11.4 ppm°C<sup>-1</sup>), dentin (8 ppm°C<sup>-1</sup>), amalgam (25 ppm°C<sup>-1</sup>), and composite resin (25–60 ppm°C<sup>-1</sup>),<sup>72</sup> which may lead to the creation of gaps and subsequent microleakage after thermocycling.

Thermocycling significantly reduced bond strength due to difference in the coefficient of thermal expansion leading to gap creation, which will lead to microleakage.

### *Water Storage/Aging*

Saiku et al<sup>59</sup> compared the effect of aging on the microleakage of bonded amalgam at 24 hours and 30 days using Amalgambond, copal varnish, and no lining. They showed that non-aged Amalgambond-lined teeth showed significantly less microleakage than after aging for both resin/enamel and resin/dentin interfaces. The increased microleakage shown in the aged Amalgambond-lined restoration suggests that interfacial resin may undergo hydrolytic degradation, indicating a level of resin liner breakdown. Nakabayashi et al<sup>24</sup> suggested that after long-term immersion in water, deterioration of the 4-methacryloyloxyethyl trimellitate anhydride (META) adhesion occurs in a band of exposed collagen that lies between the “hybrid” dentin layer and the unaltered dentin. Ben-Amar et al<sup>73</sup> also showed that after aging with water, microleakage significantly increases.

Water storage significantly increases microleakage of the restoration margins.

### *Spherical vs Admixed Amalgam*

Several studies examined the effects of different amalgam alloys on microleakage with various dentin bonding agents or resin liner systems. Turner et al,<sup>58</sup> Tangsgoolwatana et al,<sup>60</sup> and Korale and Meiers<sup>49</sup> found that the choice of alloy had no significant effect on the microleakage scores. On the contrary, Mahler and Nelson<sup>74</sup> showed that spherical alloy (Tytin) had a greater tendency for marginal microleakage than admixed alloy (Dispersalloy). Helvatjoglou-Antoniades et al<sup>71</sup> compared Orosphere Plus (admixed), Indiloy (spherical), Oralloy (spherical), and gallium. They found that Oralloy has a significantly higher microleakage when compared with the other three alloys and suggested that it was due to the high tin content of Oralloy which affected the dimensional stability.

Spherical amalgam alloys have a significantly higher microleakage.

### *Resin-lined vs Dentin Bonding Agents Alone*

Most of the earlier studies employed only dentin bonding primers prior to amalgam condensation for testing

microleakage.<sup>49</sup> Turner et al<sup>58</sup> demonstrated that using the dentin bonding primer and resin bonding may help to reduce microleakage which may minimize the risk of recurrent caries or postoperative sensitivity. Korale and Meiers<sup>49</sup> duplicated the microleakage study of Turner using the same bonding systems, but without the viscous liners. They showed that dentin bonding primer restorations had significantly less microleakage at both the occlusal and gingival margins than Copalite and unlined restorations, which is in agreement with Berry et al.<sup>54</sup> They also concluded that the rationale for using dentin bonding agent with amalgam is to prevent microleakage, while the addition of the resin liner is to form mechanical interlocking with the amalgam in order to aid in amalgam retention.

Berry et al<sup>54</sup> compared the microleakage of etched and nonetched class I occlusal amalgam restorations. These were treated with different dentin bonding system primers. They found that acid-etched restorations permitted significantly less microleakage than Copalite, nonetched, and unlined restorations.

Dentin bonding agent helps to reduce microleakage, while the use of resin cements increases bonded amalgam bond strength.

#### *Dual-cure vs One-bottle Adhesive*

Briso et al<sup>55</sup> in their study concluded that dual-cured adhesives reduced microleakage around amalgam more effectively than "one-bottle" adhesives. However, only one of the dual-cured cements, Scotchbond Multipurpose Plus, showed significantly better control of dye penetration, while the other two dual-cured cements performed similarly to the "one-bottle" cement.

There are mixed results with dual-cure adhesives generally showing reduced microleakage.

#### *Bond Strength and Microleakage*

Muniz et al<sup>47</sup> have shown that there is no positive correlation between sealing and retention properties of adhesives. Although differences between adhesives were found for bond strength testing, the microleakage evaluation failed to demonstrate a relationship.<sup>18,75-77</sup> This seems to suggest that there is no correlation between sealing and retention.

There is no positive correlation between sealing and retention of restorations.

#### *Resin-modified Glass Ionomer*

da Silva et al<sup>78</sup> found that resin-modified glass ionomer produced the lowest leakage in cementum/dentin margins when compared with copal varnish and resin cements (RelyX ARC, Single Bond and Alloybond). They

explained that this could be attributed to the high dimensional stability of the material, lower thermal conductivity, as well as chemical adhesion to dentin.<sup>6</sup> Other studies also agree with da Silva et al<sup>78</sup> that RM-GIC produced the lowest leakage.<sup>6,79,80</sup> de Moraes et al<sup>80</sup> also found that resin-modified glass ionomer significantly decreased microleakage and was shown to perform significantly better than Panavia Ex.

Resin-modified glass ionomer produced the lower microleakage compared with resin cements.

### **Clinical Studies**

#### *Complex Amalgam Restorations: Pins vs Bonded*

In a prospective clinical trial comparing 60 bonded and amalgam pin-retained complex amalgam restorations after 5 and 6 years, failures were reported for eight pin-retained and three bonded restorations.<sup>81,82</sup> No significant differences in failure rate, marginal adaptation, marginal discoloration, secondary caries, tooth sensitivity, or tooth vitality were found. The authors concluded that bonding with a filled, 4-META-based bonding resin appears to be a viable alternative to dentin pins.

In a shorter study of 2 years' duration, Amalgambond Plus used with or without HPA was compared with dentin pin-retained restorations.<sup>83</sup> All restorations were "completely retained and rated alpha." These authors also concluded that amalgam adhesive is an alternative to pins, although the study was only short term.

Davis and Overton<sup>84</sup> compared bonded amalgam with pin-retained amalgam in teeth with "incomplete fractures" and reported that both treatments were successful in reducing chewing sensitivity in "cracked molars" up to a period of 1 year. They suggest that bonded amalgam may be preferred over mechanically retained complex amalgam restoration with incomplete fracture; however, this study was not a long-term review.

Amalgam bonding can successfully retain large restorations and reduce chewing sensitivity.

#### *Postoperative Sensitivity*

Postoperative sensitivity following amalgam restorations is a possible sequelae to this dental treatment and it negatively affects the patient's dental experience. It has been considered to occur due to microleakage around the restoration.<sup>85</sup> However, over time, corrosion products are thought to seal the restoration, reducing microleakage and so reducing the sensitivity.<sup>86</sup>

A long-term double-blinded study by Smales and Wetherell<sup>87</sup> reviewed other studies on the clinical performance of 366 premolar and molar bonded amalgam restorations placed in classes I and II cavities with five dentin/amalgam bonding agents over a period of up to

5 years. Five restorations failed and no pulpal sensitivity or recurrent caries were reported. They reported that the use of “adhesive lining materials may offer few long-term advantages over non-bonded amalgam restorations.” However, there was no comparison with nonbonded restorations in their analysis, so one may question their conclusion.

Mahler et al<sup>88</sup> investigated the use of Panavia 21 on 100 classes I and II amalgam restorations, and reported no benefits for the bonded restoration with regard to marginal fracture and short-term postoperative sensitivity after 1 year. The same author<sup>9</sup> performed a follow-up evaluation at 3 years. They found no significant differences in postoperative sensitivity and marginal fracture between bonded and nonbonded restorations.

Patient symptoms were investigated in a double-blinded randomized clinical trial comparing Amalgam Bond Plus and Copalite with Vitrebond, among 60 class I and II restorations of different depths.<sup>89</sup> Cold response measures and self-reported questionnaires suggested that those who had bonded (Amalgam Bond Plus) restorations were less sensitive to cold stimulus 1 week after treatment compared with baseline. Subjects with Liner and Vitrebond (Copalite/Vitrebond) were more sensitive after 1 week compared with the baseline. Therefore, the authors concluded that Amalgambond can reduce sensitivity to a stimulus.

In a double-blinded clinical trial examining postoperative cold sensitivity, Browning et al<sup>89</sup> evaluated the use of OptiBond in class I or II amalgam restorations of different depths, and were unable to observe significant differences with a control group 1 week after treatment. It was concluded that OptiBond does not reduce sensitivity to a stimulus. Similar results were also reported in two additional studies that evaluated postoperative sensitivity<sup>90,91</sup> with OptiBond.

Subay et al<sup>92</sup> investigated the pulpal response to Scotchbond Multipurpose Plus bonding agent in non-carious class V cavities. A traditional class V cavity was performed on premolars of patients who were undergoing orthodontic treatment and were extracted after 10 and 35 days. While histological examination showed that Scotchbond multipurpose Plus did “not exhibit significant deleterious effects on the human pulp tissue during the test period,” it caused more pulpal reaction than dycal with zinc oxide and eugenol restorations, although no statistical analysis was performed.

Studies’ results were controversial, some found to have no difference in postoperative sensitivity between bonded and nonbonded amalgam restoration while others found Amalgambond restoration to reduce postoperative sensitivity.

## DISCUSSION

This article systematically analyzed the performance and clinical success of bonded amalgam restorations. The PubMed database was used and the reference list for bonded amalgam featured 465 articles of which 170 articles were selected for the systematic review. While the *in vitro* studies focused on shear bond strength, tensile bond strength, and microleakage of bonded amalgam restorations *in vivo* studies were primarily on postoperative sensitivity. The results of this study seem to support that the bond strength of amalgam bonded restorations has similar clinical outcomes to nonbonded restorations. However, addition of filler particles, light-cured adhesives, and the use of spherical alloy resulted in higher shear bond strength. The tensile bond strength was increased when the amalgam was allowed to set prior to its adhesion to dentin. The results of our analysis showed reduced microleakage when dentin bonding agents and RM-GIC were used as adhesives. However, the use of spherical alloys, aged amalgam bonded restorations, and thermocycling increased microleakage of the restoration margins. The analysis of *in vivo* studies showed that amalgam adhesives were preferred over pins for retaining complex restorations and the postoperative sensitivity was similar for both bonded and nonbonded amalgam restorations.

For generations, dental amalgam has been considered as the clinically preferred primary restorative material in areas of the mouth where esthetics is not of concern due to its excellent physical properties, safety, efficacy, and longevity.<sup>93</sup> There have been, however, controversies and debate regarding the use of amalgam in dentistry due to potential mercury release and its adverse effects on health and the environment. This has led practitioners to explore alternative dental restorations.<sup>11</sup> Studies by Risher<sup>94</sup> and Dye et al<sup>95</sup> have reported that an increased number of amalgam restorations in children resulted in increased urinary mercury concentrations which would be of concern as prolonged exposure may lead to renal, neurological, and immunological impairments. However, several other studies assessed the health effects from mercury exposure related to dental amalgam and did not report any significant adverse effects.<sup>96,97</sup>

The use of amalgam has declined in higher income countries<sup>93,98,99</sup> and it has also been banned in countries like Norway,<sup>100</sup> Sweden,<sup>101</sup> and some states in the United States, as they considered mercury release from amalgam restorations to be a dangerous environmental toxin. In other parts of Europe, countries like Denmark, Italy, Finland, and Estonia use amalgam restorations for less than 5% of carious lesions.<sup>102</sup> Amalgam restorations have been used restrictively in Japan and Switzerland.<sup>102</sup> A

number of other countries like France, Austria, Canada, Finland, and Germany have also minimized the use of amalgam restorations, restricting their use in pregnant women, in children under 6 years of age, and in patients with kidney problems.<sup>103</sup>

Several studies have reported a lack of evidence of any adverse health effects on clinicians handling amalgam and the patients who receive it. It has also been stated that the residual mercury disposal does not contribute to a significant source of environmental mercury.<sup>104</sup> This was supported by several organizations like World Health Organization (WHO), World Dental Federation (FDI) and International Association for Dental Research, as a ban on amalgam would result in substantial increases in oral health disparities.<sup>105</sup>

While in 2009, at the FDI at the general Assembly, amalgam was stated as being a safe restorative affordable material for the majority of communities around the world who are in need of dental treatment,<sup>105</sup> it later described in a policy statement the intent to phase down the use of dental amalgam.<sup>106</sup> The elimination or phase-out of amalgam in dental restorations was first proposed by United Nations Environment Programme in collaboration with WHO<sup>93</sup> to eradicate the release of mercury vapors and other by-products during the manufacture, processing, and transport of mercury. However, the term "phase-down" was adopted to replace "phase-out," as complete elimination of amalgam requires developing an alternative material with better properties for use. The Minamata Convention on Mercury conducted in 2013 put forward nine provisions on dental amalgam to lead to a worldwide reduction in mercury release into the environment.<sup>106</sup> The Minamata convention also proposed a ban of mercury-containing nondental products and to phase out the use of dental amalgam by 2020 to protect human health and the environment from mercury toxicity.<sup>13,107</sup>

The trend toward mercury-free dentistry by phasing down and eventually phasing out dental amalgam has forced dentists all over the world to consider using an alternative restorative material. Unfortunately, these alternatives are expensive and so the potential cost incurred by the patients has raised concerns regarding the implication of dental health care, especially in underdeveloped and developing countries. A ban on amalgam restorations is expected to have a financial impact on both dentists and patients. Most often, people from urban areas and higher income groups are not affected due to decreased oral health needs and increased accessibility to dental health care. However, the most heavily affected populations will be those of lower and middle socioeconomic strata having poor oral health,<sup>108</sup> as they will have no other option but to choose the more expensive composite restorations which have a reported lower longevity than amalgams.<sup>109</sup>

This may lead to increased restoration replacement and associated financial and biological costs, or patients not seeking required dental care, leaving caries untreated or requiring tooth extraction, both of which may leave the patient in distress. Hence, a complete ban on amalgam would adversely affect the oral health of lower socioeconomic populations, as a lack of financial resources to afford composite may mean extraction of restorable teeth.

While composite resin restorations have been adopted as an alternative restorative material in most countries, they pose biocompatibility issues through the release of toxic substances from the components of restorative material.<sup>110</sup> Concerns have been revolving around the release of bisphenol A (BPA) from composite restorations. They are reported to have cytotoxic effects which may lead to pulp irritation and gingival inflammation,<sup>111</sup> as well as potential effects on chromosomes, resulting in several systemic complications.<sup>111,112</sup> Despite the evidence that BPA and other toxic substances leach from composite resins, these restorative materials are used almost globally, which could probably be due to the existence of BPA in most of the plastic products and household appliances used on a daily basis. Hence, the use of composite as an alternative to dental amalgam cannot be conclusively justified, and the potential long-term effects of these alternative dental materials should be thoroughly examined before considering the complete phase-out of conventional amalgam restoration.

Despite the desire and need to reduce amalgam use based on environmental concerns and move toward mercury-free restorations, there is a high cost involved both financially and potentially biologically. This means that amalgam restorations will continue to be necessary for the treatment of dental caries in regions of the world with limited dental resources and in population groups with health financing challenges, and as such, amalgam will remain a necessary restorative material for the foreseeable future.

## CLINICAL SIGNIFICANCE

The use of adhesives to bond amalgam to the tooth structure offers potential advantages, although there is inconsistency in results when compared with nonbonded amalgam. However, bonded amalgam helps in conservative cavity preparation without compromising the retention to tooth, making it a material of choice in large posterior restorations.

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