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In Vitro Bond Strengths of Amalgam Added to Existing Amalgams

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Clinical Relevance

Freshly mixed amalgam added to existing amalgam restorations as a means of repair and allowed to set completely may be expected to join with nearly original strength, if sufficient condensation time and pressure are used.

SUMMARY

This study determined if a standardized condensation force and dwell time per condensation pressure point could reliably bond new amalgam to older amalgam without applying extrinsic Hg. A stabilization jig was created to hold 15 friction-fit 1-inch diameter (25 mm) cylindrical resin specimen blocks face up with cavities drilled to contain the condensed primary amalgam (Valiant PhD-XT). Freshly mixed secondary amalgam (Valiant PhD-XT) was condensed against the primary amalgam surfaces through the 3.5-mm-diameter central holes of specially fabricated split-ring molds. The 15 disks fit snugly within the holes of the stabilization jig tray. Condensation was with a consistent, calibrated force of 22.5 MPa (4 lbs/0.79 mm^2) applied with a spring-loaded amalgam carrier custom adapted with a 1-mm-diameter stainless steel condenser tip. Secondary amalgam additions were built up in three 1-mm thick increments with a pattern of eight 22.5 MPa two-second condenser strokes per incremental layer. Shear-bond testing with a 1-mm/minute crosshead speed occurred 24-hours post-condensation. One-way analysis of variance statistical analysis was conducted to analyze the results. The mean shear-bond forces (MPa, N=15) found were: Control 28.1 ± 5, 15 minutes 31 ± 5, one hour 10.7 ± 4 (N=30), one day 25.5 ± 4, one week 25.2 ± 4, two months 25.1 ± 5 and seven years 24.7 ± 4.

Under the condensation pressures used in the current study, the addition of new amalgam to smooth previously set amalgam surfaces, not including the one-hour group, up to seven years old, resulted in shear-bond forces not statistical-

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ly different (*p*=0.05) from the intact control. Virtually all (94%) of the bonds tested, except for the one-hour sample, resulted in cohesive rather than adhesive failures except those of the one-hour sample. Forty percent bond strengths of the controls were achieved when only 5.6 MPa (1 lb/0.79 mm²) and 14 MPa (2.5 lb/0.79 mm²) condensation pressures were used.

INTRODUCTION

Amalgam as a restorative material continues to play a significant role in dentistry as evidenced by the fact that approximately 68% of US dentists surveyed by Clinical Research Associates in 2005 reported using dental amalgam in their practice.[1] Considerable time and expense for both operators and patients might be saved if amalgam restorations could be routinely repaired or added to in some manner, similar to resin composite material.[2]

Several studies have examined the feasibility of repairing set amalgam with directly applied fresh amalgam, with varied results. In 1968, Jorgensen and Saito obtained essentially 100% repair bond strength by burnishing free Hg to the amalgam surface.[3] This use of free Hg, however, is not considered a viable option due to potential direct and indirect environmental contamination involving dental offices.[4]

Nettelhorst[5] reported transverse strengths of repaired amalgam between 20% and 52% of unrepaired control samples. This strength range may be on a par with that of resin composite because, although commonplace in dentistry, resin composite repairs were found by Söderholm to possess less than half the strength of the original unrepaired composite, even under the most ideal conditions.[6]

Partly due to lack of standardization, recommendations as to whether previously set amalgam restorations could be repaired have been equivocal. Previous literature studies have not specifically accounted for the thickness of additional increments, condensation forces and the dwell time of condenser thrusts used for direct amalgam repairs. A satisfactory method is desirable without using free Hg or special instruments.

The current study was undertaken to take these factors into account and ascertain the feasibility of direct amalgam repairs. Experimentation involved creating a stabilization jig to hold added portions for testing and devising a calibrated condenser to apply a consistent measured force. Cohesive forces of repaired amalgam specimens were recorded 24 hours after: 1) initial condensation, 2) 15-minute, 3) 1-hour, 4) 1-day, 5) 1-week, 6) 2-month and 7) 7-year addition intervals.

The null hypothesis for this study was that there are no statistically significant differences in the measured interfacial shear-bond forces of specimens prepared by bonding freshly mixed amalgam to different ages of existing palladium-enriched/high copper dispersed phase dental amalgam.

METHODS AND MATERIALS

Poured-resin (polymethyl methacrylate polymer #003-07-0358, monomer #871-06-0719, Esschem Co, Linwood, PA, USA) 25-mm (1-inch) diameter cylinders approximately 20 mm in height were prepared in a polyoxymethylene (Delrin, POM) 15-hole specimen mold (Part #1599, Ultradent Products, Inc, South Jordan, UT, USA).

To serve as repair amalgam condensation molds, 15 5-mm thick POM disks were machined to 25-mm diameter with 3.5-mm diameter centered holes, with each disk receiving a bisecting cut to produce two halves (Moran Innovations, Inc, Redlands, CA, USA).

Faces of the solid poured-resin cylinders were machined perpendicular to their outside walls. Holes to serve as cavity wells for the amalgam were drilled 3.5-mm deep in the center of the flat face, similar to Jessup and others,[7] using a machine lathe with a 6-mm diameter drill bit.

The apparatus consisted of 15 poured-resin cylinders fully inserted into the 15 holes of the polytetrafluoroethylene molding tray, with 15 split-ring POM disks snugly seated into the recessed area of the same holes on top of the cylinders (Figure 1). Each inserted cylinder was at least four mm below the surface of the molding tray, providing space to seat each disk. This tray of specimens was secured to a flat metal platform to stabilize the assembly.

A standard amalgam carrier (stainless steel, double-ended; Pulpdent Corporation, Watertown, MA, USA) was adapted to serve as the calibrated amalgam con-

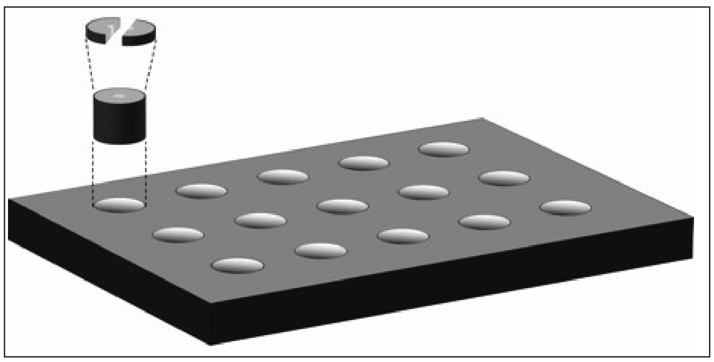

Figure 1: *Diagrammatic representation of the Ultradent resin cylinder mold used as a tray to hold specimens during repair amalgam condensation. The split-ring molds fit securely into the recessed spaces on top of the cylinders to stabilize the repair columns until testing. The specimen mold assembly tray with 15 specimens was clamped to a steel underplate for stability.*

Figure 2

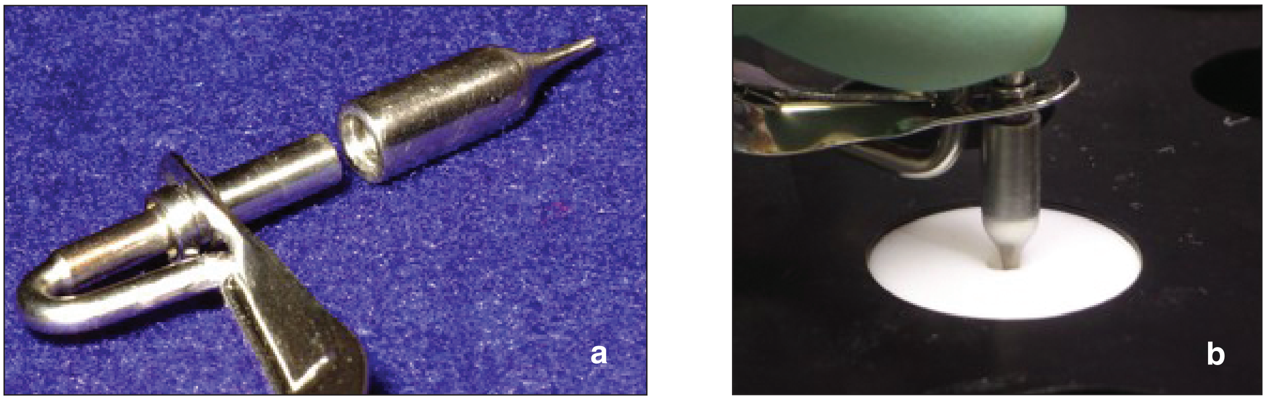

Figure 2a: *A 1-mm diameter stainless steel condenser tip machined to fit as an oversleeve on the large end of the amalgam carrier, shown detached;* Figure 2b*: The amalgam carrier spring tension was increased to four pounds calibrated when the barrel reached the end of the piston shaft. The condenser apparatus is shown condensing a specimen at full play through the split-ring mold.*

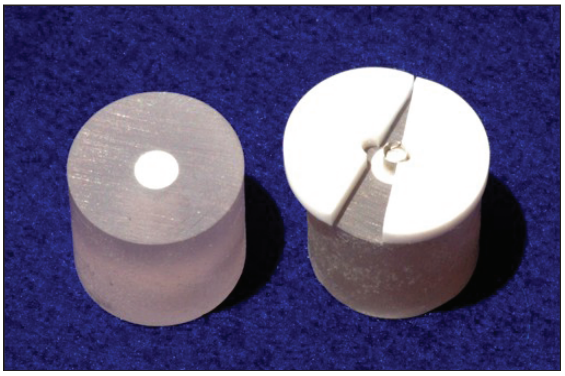

Figure 3: *Within the 3.5 mm diameter circle, the 1-mm diameter round condenser tip placed seven times around the perimeter and once in the center provided thorough condensation.*

denser. In order to standardize the condensation force, the carrier's spring tension was increased by bending it to a tighter curvature. This tension was calibrated on an analog gauge (#2780 block pressure gauge, Mitutoyo, Kawasaki, Japan) to a force of 4 lbs (17.6 N), measured when the carrier sleeve was fully depressed. Two more amalgam carriers were calibrated in a similar fashion to a force of 1 lb and 2.5 lbs made to condense other samples in this study for comparison with the 4-lb force samples.

A special nib was machined from stainless steel (Moran Innovations, Inc, Redlands, CA, USA) to fit over the large end of the amalgam carrier (Figure 2a). This had a 1-mm (0.79 mm^2) diameter nib 5 mm long, with a flat, non-serrated tip allowing for condensation of secondary amalgam in the 5-mm-deep holes of the split-ring molds (Figure 2b). The resulting pressure per condensation stroke with this tip was 22.5 MPa (17.8 N per 0.79 mm^2). To reduce unnecessary variation, all the specimens were condensed by the same operator (primary author) throughout this study.

Pre-encapsulated amalgam (Valiant PhD XT Sure-Caps, 600 mg, Ivoclar-Vivadent, Inc, Amherst, NY, USA, Lot #+$H34363 D1201XW) was obtained from stock currently used at the local dental clinic. These capsules were mixed using a triturator (Silamat, Ivoclar Vivadent) at eight seconds per capsule. The fresh mix of amalgam was thoroughly hand-condensed into the 6-mm-diameter cavities of the solid resin cylinders using a non-serrated 1.5-mm-diameter amalgam condenser (Suter SS #UP1-2, Chico, CA, USA).

Each specimen cavity well was overfilled by at least 1 mm and the excess Hg-rich layer carved level with the cylinder face using a single-edge razor blade held at a low angle to make a smooth pass across the surface. This provided a uniform surface similar to what a carver or rotating bur would create, to which the secondary 3.5-mm-diameter amalgam test columns would subsequently be condensed (Figure 3). The resin-cylinder mold tray containing 15 holes was used as the holding rack, secured to a flat metal underplate (Figure 1).

Specimens that were prepared to receive later amalgam columns were stored at 37°C until the secondary amalgam was added. The seven-year specimens that had been stored at room temperature (20°C -23°C) were the only ones that came from a different batch of Valiant PhD-XT.

In vitro specimens from the two-month and seven-year samples required light oxide layer removal to return their surfaces to fresh-cut characteristics. This was accomplished with wet 320-grit silicon carbide paper (Buehler Carbimet paper roll, #30-5143-320-001, Buehler Ltd, Lake Bluff, IL USA). These surfaces were immediately rinsed with deionized water to eliminate possible contaminants and the specimens were stored at 37°C until tested.

The general study design involved seven sample groups with amalgam columns condensed at intervals as follows: 1) Control with primary and secondary amalgam condensed simultaneously, 2) 15 minutes, 3) one hour, 4) one day, 5) one week, 6) two months (70 days) and 7) seven years.

At each of the above intervals, freshly triturated amalgam was condensed through the split-ring disk center holes. The initial amount introduced was half the load capacity of the smaller end of the carrier, as recommended by Consani and others.[8] This first increment was tamped into place with the 1.5-mm diameter condenser, producing a relatively even thickness of approximately 1 mm. Using the same condenser in a circular stirring pattern three times counterclockwise and three times clockwise with a force of 1-2 lbs (4.4 to 8.8 N), intrinsic Hg was mobilized from the fresh amalgam to wet the primary amalgam layer.

Employing the calibrated spring-loaded amalgam carrier fitted with a customized 1-mm diameter stainless steel condenser tip, a slight 10-degree arc-rocking motion, left-right-left-right for two seconds, was applied per condensation stroke. Secondary amalgam column additions were condensed in three total increments with a pattern of eight two-second condenser strokes per layer. This consisted of seven condensation strokes around the perimeter and one in the center (Figure 4) at 22.5 MPa per condensation stroke by the same operator.

These condensation forces, each held for two seconds per stroke, allowed intrinsic Hg from the pre-encapsulated fresh amalgam to be pressed or infused into the surface of the recipient amalgam to facilitate the union or bond. The next increment of amalgam was likewise half the capacity of the smaller end of the amalgam carrier and received the same force and pattern of condensation thrusts. A third half-load increment, after similar condensation, brought the final height of each repaired-amalgam column to approximately three and one-half mm.

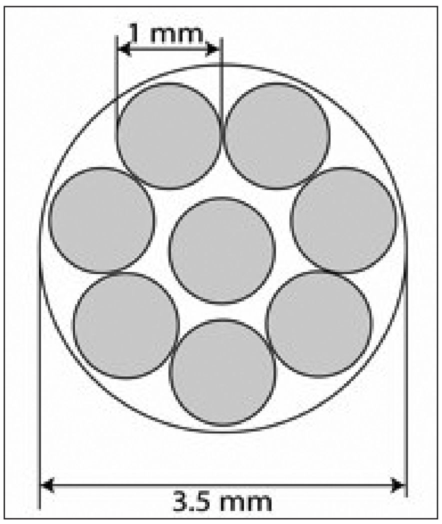

Figure 4: *Within the 3.5-mm diameter circle, the 1-mm diameter round condenser tip placed 7 times around the perimeter and once in the center provided thorough condensation.*

With the extended-time (XT) formula of amalgam tested, setting was slow enough that three secondary amalgam specimens could be condensed from one 600 mg capsule.

At the time of testing, the POM mold serving as the holding tray for the 15 specimens was removed from the incubator. The resin specimen cylinders were each pushed up from the bottom and ejected carefully through the top of the tray with the individual split-ring disks intact. Disk halves were then teased apart to leave the standing columns of amalgam (Figure 3). Any inadvertent flash of amalgam at the base of the columns was cleanly removed with a single-edged razor blade.

Sample fracture testing was conducted with a testing machine (ReNew Model 1125 Upgrade Package, MTS Systems Corporation, Eden Prairie, MN, USA) using a 500 N load cell and a crosshead speed of 1 mm/minute. Peak fracture forces in pounds were measured 24 hours post-condensation. One-way analysis of variance (Statistics Package for the Social Sciences, Version 16.0, SPSS Inc, Chicago, IL, USA) was conducted to analyze the results. The fracture sites were analyzed under five power binocular microscopic magnification and categorized according to the following criteria in accordance with Diefenderfer and others.[9-10] Separation at the interface = A (adhesive), >3/4 cohesive failure = C (cohesive), <3/4 cohesive failure = M (mixed); fractures involving the primary amalgam surface = 1, those involving the secondary amalgam surface = 2 and those involving both surfaces = 1+2 (see Table 1).

In order to estimate the influence of lighter condensation forces and less condensation-point holding time relative to the control sample, the following tests were conducted:

1. To assess the value of a lower condensing load force for amalgam repaired at 24 hours, a sample was tested following the same procedure except using only a 1 lb condensation force, 5.6 MPa (1 lb/0.79 mm^2) instead of 22.5 MPa (4 lb/0.79 mm^2) was used for the control.
2. The same procedure was followed using 2.5 lbs/0.79 mm^2 (14 MPa) of condensation force.
3. The relative influence of reduced cumulative condensation-force holding time was tested using only one series of eight condensation thrusts, as shown in Figure 4, compared with three series of thrusts.

RESULTS

The resulting mean shear-bond forces for the 15-minute, one-day, one-week, two month and seven-year samples were not statistically different (p=0.05) from the intact control group (Figure 5).

Even though strict protocol was followed, the mean sample bond strength of 10.5 MPa (22.7 lbf/0.79 mm^2) for the one-hour sample was markedly lower than the other times studied. This lower value was subsequently confirmed upon carefully repeating the test sample and obtaining 10.9 MPa (23.6 lbf/0.79 mm^2).[11] The results of these two were not significantly different and were combined to an average mean of 10.7 ± 4 MPa (23.1 ± 8 lbf/0.79 mm^2, N = 30) (Table 2).

The results of the influences of a lighter condensation force and less time were as follows:

1. Using only a 1 lb condensation force, 5.6 MPa (1 lb/0.79 mm^2), instead of 22.5 MPa (4 lb/0.79 mm^2), resulted in an approximately 39% mean decrease from the control 28.1 ± 5 MPa (60.8 ± 10 lbf/0.79 mm^2, N = 30) to 17.1 ± 2 MPa (37 ± 5 lbf/0.79 mm^2) and a 33% mean decrease in repair force from the 24-hour mean 25.5 ± 4 MPa (55 ± 9 lbf/0.79 mm^2). Only five of the 15 specimens of these shear-bond interfaces exhibited cohesive failures (Figure 7 and Table 3).

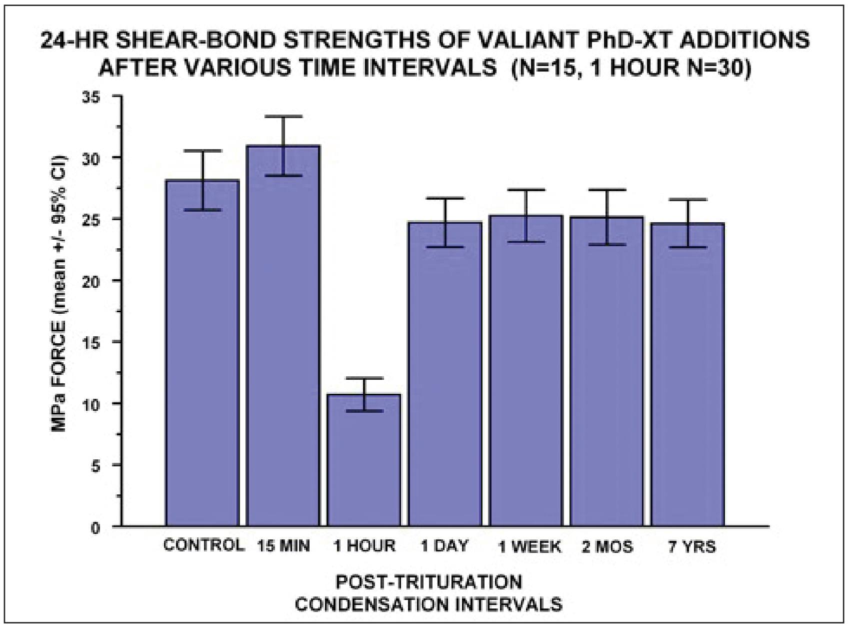

Figure 5: *PhD-XT amalgam was condensed, then repaired with the same type amalgam at intervals from immediately (control) through seven years. None were statistically different from the control except the one-hour sample. Ninety-five percent confidence intervals are shown in brackets on each bar.*

2. Using 2.5 lbs/0.79 mm^2 (14 MPa) condensation force, 14 MPa (2.5 lb/0.79 mm^2), similarly resulted in a 39% mean decrease from the 24-hour control. The one-day repair sample mean of 35.5 MPa, as shown in Figure 7, was chosen for comparison, because it similarly received 48 seconds of pressure-holding time; whereas, the original control, since its condensation necessarily involved rapid continuous buildup, did not. Of these specimens, 13 had cohesive, one had mixed and one had adhesive failures (Table 3).

3. Reducing the total condensation pressure holding time to only 16 seconds instead of 48 seconds resulted in an approximately 24% mean reduction in repair strength from 25.5 ± 4 MPa (55 ± 9 lbf/0.79 mm^2) to 19.4 ± 5 MPa (41.9 ± 10 lbf/0.79 mm^2) (Figure 7 and Table 3). Approximately three-fourths of the bond strength was obtained from the first series and the remaining one-fourth was

Table 1: *Fracture Surface Analysis Code Key Extended From Diefenderfer & Others[9] and Sneesby & Meiers[10]*

Mode of Fracture	Code	Description
Separation at interface	A	Adhesive
>3/4 cohesive failure	C	Cohesive
<3/4 cohesive failure	M	Mixed
In primary (1°) amalgam	1	Primary (1°) failure
In secondary (2°) amalgam	2	Secondary (2°) failure
In both 1° and 2° amalgams	1+2	Both 1° and 2° failures

Table 2: *Mean Shear Bond Strengths in MPa are Shown for Each of the Sample Groups From the Intact Control Through Seven Years, Including the Codified Modes of Bond Failure (see Table 1 for key)*

(N=15, N=30 for 1 Hour)	Control	15 Minutes	1 Hour	1 Day	1 Week	2 Months	7 Years
Mean Shear-Bond Strengths (MPa)	28.1 ± 5	31 ± 5	10.7 ± 4	25.5 ± 4	25.2 ± 4	25.1 ± 5	24.7 ± 4
Fracture modes	C1 =15	C1 =15	M1 = 1 M1 + 2 = 1 A = 28	C1 = 11 M1 = 3 M2 = 1	C1 = 15	C1 = 14 M1 = 1	C1 = 15

Note: Bulk fractures (C1) were generally associated with stronger unions above 25 MPa and nearly absent in the one-hour group with only 10.7 MPa shear-bond strength, which showed predominantly (93%) adhesive failures. M1+2 indicates when both a small portion of the added secondary amalgam column base remained (M2) as well as a small part of the primary amalgam surface lost (M1) due to cohesive fractures.

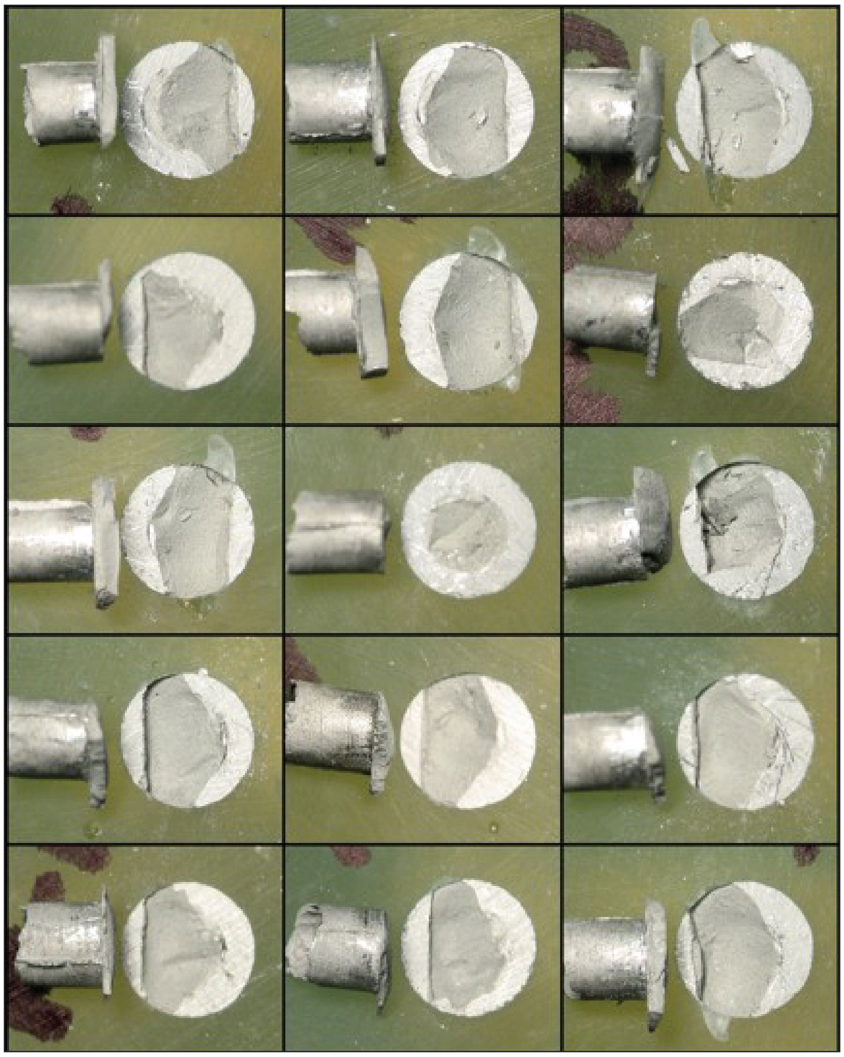

Figure 6: *The 15 specimens from the two-month (70 day) sample shown in sequential order with their fractured columns alongside, all exhibiting C1 cohesive type fractures.*

obtained from the additional two series of condensation strokes.

DISCUSSION

Kirk,[12] using clinical rather than laboratory condensation conditions, found that approximately one-third of the amalgam repair specimens tested had a tensile strength minimally inferior to the normal tensile strength of amalgam. Other references have also indicated high repair bond strengths relative to controls of up to 116%,[13] 100%,[9] 98%[3] and 92%.[14]

The first to demonstrate bond strengths comparable to intact controls (between 90% and 98%) were Jorgensen and Saito in 1968.[3] In order to achieve high test values, these investigators used a laboratory machine that applied a load of 40 kg to a 5-mm-diameter piston-like condenser and held this pressure of 2,900 psi (20 MPa) for three minutes. Although such an apparatus would be inappropriate in a clinical setting, the successful principles of pressure and time of application can still be carried out in practice. The condensation pressure of 40 kg per 5 mm diameter corresponds to a force of 3.52 lb (15.5 N) on a condenser 1 mm in diameter (0.79 mm^2) as used in the current study. These investigators burnished or rubbed a 3:2 (7.5:5) ratio Hg:alloy mix of amalgam for 5-10 seconds in order to wet the surface with Hg. More recent studies, however, indicate this was probably an insignificant aid to bond strength. An Hg-rich surface was reported by one investigator as effective,[15] but others found it to be of no significant improvement[5] or of little benefit[16] and not appropriate to use regarding Hg hygiene consideration.[17] More likely related to success is the combination of pressure plus condensation holding time to allow intrinsic Hg from the fresh repair mix to infiltrate the primary (original) amalgam surface.

The current study used a condensation pressure of around 22.5 MPa, which is roughly comparable to that of Jorgensen and Saito,[3] Brown and others[18] and Walker.[19] Instead of a three-minute holding time, the laboratory in the current study used 48 seconds per specimen. Condensation occurred in three increments, requiring eight patterned thrusts each held for two seconds, providing a cumulative total of 48 seconds of pressure holding time per 3.5-mm diameter repair specimen. The combination of pressure and dwell time may have allowed available Hg from the donor amalgam to penetrate and re-initiate the reaction-phase setting of the older amalgam. The resulting 15-minute, one-day, one-week, two-month and seven-year bond strengths were consistent with that of Jorgensen and Saito[3] relative to the intact control. These authors reported that, although primary amalgam strengthened logarithmically in a straight line from the time of condensation to 24 hours, repair (secondary) amalgam gained strength more slowly, exhibiting less than half the strength of original unrepaired amalgam at intervals through the first 12 hours, followed by an exponential rise thereafter to 24 hours. At the 24-hour point, the repair amalgam still was not fully set, with transverse flexural tests showing its strength to be only 88% of the unrepaired amalgam control. Results from the current shear-bond test study paralleled this percentage at 24 hours, with around 25 MPa (53-55 lbf/0.79 mm^2) for the one-day, one-week, two-month and seven-year samples compared to nearly 28 MPa (61 lbf/0.79 mm^2)

for the control. Due to the delayed setting curve for repair amalgam, it could be that, had the samples from the current study been tested a few days later, they would have more nearly equaled the control strength.

The markedly reduced bond strength of the one-hour sample may have to do with the early weakness of union of around 12% of final strength, as noted by Jorgensen and Saito.[3] The increased number of fractures with M1+2 classification (mixed involving both primary and secondary surfaces, Tables 1 and 3) in the 1/3 Condensation Time group may have been due to firm condensation of only the first increment imparting denser properties to the initial layer and leaving the remaining portion of the column more loosely packed. The angular plane of cleavage of four of the 15 fractures started in the secondary amalgam columns (M2) near the start of the more loosely compacted bond layer and ended in the primary amalgam (M1).

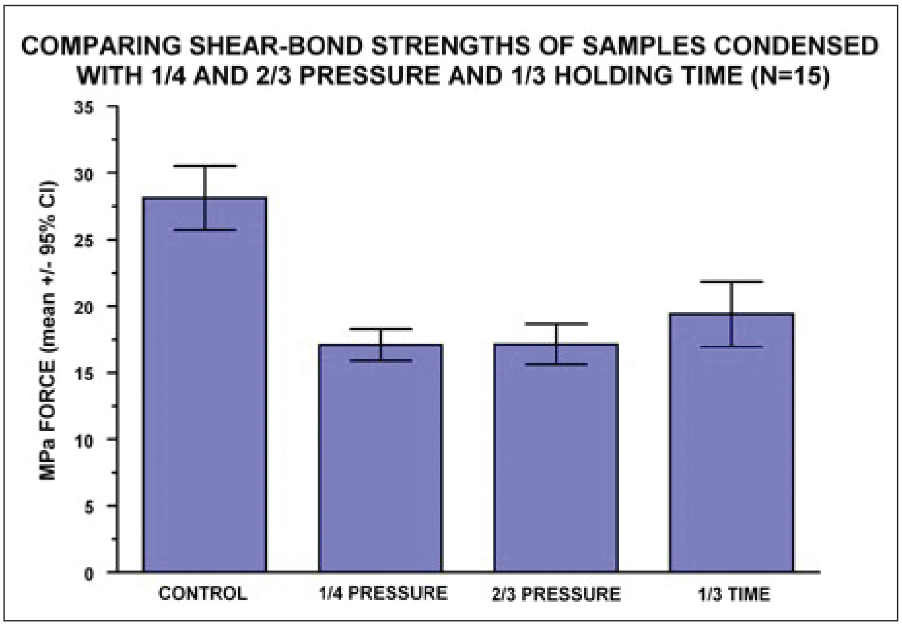

Figure 7: *Graph illustrating relative repair strengths using only 1 lb/0.79 mm² (5.68 MPa) representing 1/4 pressure and 2.5 lbs/0.79 mm² (14 MPa) representing 2/3 pressure instead of 4 lbs/0.79 mm² condensation pressure and only 1 round of 8 condensation thrusts held at 2 seconds each (total 16 seconds) instead of the 24 thrusts (total 48 seconds) reducing the cumulative condensation pressure holding time to 1/3. The three groups produced significant repair strength reductions from the control and were not statistically different from each other. This would indicate that adequate condensation pressure and sufficient condensation thrust dwell time were both important for maximum bond strength. Brackets on the bars indicate 95% confidence intervals.*

Hadavi and others[20] employed condensation thrusts varying from 815 to 4,074 psi (5.6 to 28.1 MPa), with pressure intervals of one second each on the superimposed surfaces to obtain above-average shear-bond results 50%-79% of the intact control. It would appear that the time spent holding adequate condensation pressure aided infiltration of the available expressed Hg into the older amalgam surface.

ANSI/ADA Specification No 1 requires that specimens for laboratory testing be subjected to a condensation pressure of 14 ± 1 MPa.[21] As a result, most amalgam manufacturers recommend, either explicitly or implicitly, that dental practitioners apply a condensation pressure of 14 MPa when inserting amalgam restorations.[22] This corresponds clinically to a force of approximately 2.5 lb (11 N) for a 1 mm diameter condenser, 5.6 lb (24.5 N) for a 1.5 mm condenser and 15.5 lb (68.2 N) for a 2.5-mm diameter condenser. Investigators using significantly less pressure than this may partly explain generally lower bond strengths.

The increments of fresh amalgam introduced in the current study were approximately 1 mm deep. The

Table 3: *Mean shear bond strengths in pounds, comparing results of using only 1 lb (5.68 MPa) condensation force, 2.5 lbs (14 MPa) condensation force and only 1/3 the condensation holding time (16 instead of 48 seconds/specimen) against the control. Fracture modes are also shown for each group (see Table 1 for key to codes used).*

N = 15	Control	1 lb (4.4 N) Condensation Force	2.5 lb (11 N) Condensation Force	1/3 Condensation Holding Time
Shear-Bond Strengths (MPa) at 24 hrs (Mean ± SD)	28.1 ± 5	17.1 ± 2	17.1 ± 2	19.4 ± 5
Fracture Modes	C1 = 15	C1 = 4 M1 = 2 A = 9	C1 = 13 M2 = 1 A = 1	C1 = 6, C2 = 1 M1 = 1, M2 = 3 M1+2 = 4

Note: Modes of fracture indicated no adhesive failures in the control group, and 60% and 7% adhesive failures in the 1-lb Condensation Force and 2.5 lb Condensation Force groups, respectively. The 1/3 Condensation Holding Time group, with mean shear-bond strength intermediate between the other two, exhibited no adhesive failures. Instead, approximately half-cohesive (C1 and C2), and half-mixed (M1, M2 and M1+2) fractures.

compressed area beneath the condenser tip can be referred to as the cone of pressure due to its shape. Optimum thickness increments of amalgam are needed so that the pressure cone carries adequate pressure through it, providing a kneading action to the underlying surface. Very little compaction can be accomplished when the condenser penetrates the mass without formation of an adequate cone of compression[23] and, in order to be most effective, condensation forces should be directed perpendicular to the addition surface.[24]

Condensation pressure, even when maintained for two seconds, will be suboptimal if there is insufficient thickness of fresh secondary amalgam under the condenser tip to express available Hg. Too great a thickness of amalgam being condensed at one time would tend to dissipate condensation pressure so that the Hg expressed may not be infused as efficiently into the primary amalgam surface and potentially leave voids.

In the current study, the primary amalgam that was packed into the well molds was relatively soft and fluid. This did not allow the full pressure of condensation resulting in a somewhat higher final Hg:alloy ratio. After hardening, however, this surface did provide resistance for packing the subsequent fresh mix of repair amalgam at the full 4-lb force applied. Consequently, alloy particles in the secondary amalgam became more tightly compressed, allowing for the removal of more Hg-rich amalgam to result in a lower final Hg:alloy ratio at the interface than in the primary amalgam. As the secondary amalgam thickness accumulates with subsequent layers, it may tend to dampen further condensation pressure and the Hg:alloy ratio again increases as less excess Hg is expressed. Finkel and others[25] and Kirk[12] discovered the hardness of amalgam at the repair interface to actually be greater than areas on either side of the interface. When shear forces were applied in the current testing, the strength of the repair attachment was at least equal to the cohesive strength of the bulk amalgam to which it had been joined. As a result, specimens preferentially fractured in bulk (Figure 6) from the weaker primary amalgam side, consistent with the findings of Kirk.[12]

Although not statistically different from the control, the approximately 10% increase in mean strength shown in the 15-minute sample may have occurred because, by that time, the primary amalgam had sufficiently hardened to accept more of the 4-lb condensation force, while at the same time it was still fresh enough to allow its alloy particles to undergo further condensation. This potentially created a denser, stronger amalgam layer at the interface and on both sides, partly including the primary amalgam.

The method of shear-bond testing employed in the current study presents a limitation in that a significant component of force delivered to the test specimen is translated laterally and becomes at least partly a test of the tensile strength of the primary surface using finite element analysis, as described by Van Noort and others.[26] The tensile strength of amalgam is less than its shear strength and, under stress loads at the interface, the amalgam preferentially tends to break away from the original surface in tensile fashion.[27] Shear-bond testing as a means of comparison with control strengths up to tensile fracture limits, however, can be valid as a relative measure and all results in the current study have been listed as percentages of control values.

Essentially, all the shear-bond fractures in the six groups (excluding the one-hour sample) of Figure 5 involved bulk fracture (C1) of the primary amalgam. Failures were on a plane through the primary amalgam in a position that confirms the finite element analysis by Van Noort.[26] Bond efficiency was great enough that breakages occurred within the primary (original) amalgam surfaces significantly outside the actual bond interface. This consistent tensile fracture pattern may help to explain the similarity of average strength values for these samples. The translational forces occurring in shear-bond testing are inherently recognized as contributing to these deeper fracture patterns.[27] Typical was the two-month (70-day) sample that demonstrated consistent, extensive cohesive failures (Figure 6).

The bond between the two joined amalgams is thought to form from free Hg in the fresh mix reacting with unconsumed gamma particles in the older alloy.[19] Terkla and others[17] hypothesized that the low strength of repaired amalgam is due to a lack of potential for crystal growth on the part of the old amalgam.

The setting of dental amalgam is considered fully mature by 24 hours.[3] Since the compositional character of amalgam does not change appreciably after that, conceivably, its fusion potential would continue fairly indefinitely.[19,28] No statistically significant difference in bond strengths of the six identically repaired groups in the current study (excluding the one-hour group) indicated that the strength of the repair was not appreciably affected by the age of the amalgam, at least through seven years.

Since no thermocycling differences are likely to occur when both primary and secondary amalgam surfaces have the same or a similar thermal coefficient of expansion, no thermocycling of direct amalgam repair specimens was included in the protocol of the current study. In 1991, Hadavi and others,[29] with Tytin and Cluster amalgam, and in 1993,[30] with Tytin, reported no significant differences between thermocycled and non-thermocycled repair bonds. Roeder and others,[31] using a spherical composition Valiant amalgam, also found thermocycling not to significantly affect repair bond strength.

Valiant PhD-XT is a high-copper, phase-dispersed alloy admixture. Each Valiant PhD-XT Sure-Cap capsule contained 600 mg of alloy and 562 mg Hg. This amalgam formula permits slower setting (XT indicates "extended time"). The palladium-enriched Valiant PhD-XT alloy is wet-milled during its manufacture to reduce particle oxide formation, followed by acid-wash processing of the particles to further eliminate oxide formation from its surfaces. This would allow for a greater particle surface area to be exposed and receptive to Hg, potentially improving cohesion (personal telephone communication, Dr Tridib Gupta, chief of research, Ivoclar Vivadent Inc, Amherst, NY, USA, 7 December 2007). The extended-time formulation of Valiant PhD-XT may have also had some influence on the results on the current study, particularly with the 15-minute group.

Overall, factors for optimum condensation involve force, area of the condenser tip, thickness of fresh Hg amalgam to which the force is being applied, burnishing action to incorporate Hg into the older amalgam, dwell time of each condensation contact and type of amalgam (sizes and shapes of alloy particles and Hg:alloy ratio). It is possible that a manual sharp tapping or mechanically generated automatic vibration might aid bonding retention just as much as using greater pressure. However, two studies in the literature gave widely varying results for mechanical condensation from 0%[32] to 92%.[13]

CONCLUSIONS

Using the condensing protocol of the current study, the shear-bond strength of repaired amalgam approached that of unrepaired amalgam unaffected by the age of the amalgam undergoing repair, from 24 hours through 7 years.

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