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Amalgam Strength Resistance to Various Contaminants

C Roggenkamp • B Choi • J Chung • R Parhizkar • A Pham • R Robles

Clinical Relevance

This study provides understanding of the potential compromise of amalgam strength after maximum contamination exposure during clinical placement.

SUMMARY

Purpose: The purpose of this study was to quantify the relative strength tolerance of 1-day and 30-day amalgam following saturation contamination with water, saliva, blood, and handpiece lubricant oil during condensation.

Methods and Materials: Valiant PhD XT amalgam was tested with 300 shear-strength (N=15) and 120 compressive-strength (N=6) specimens, divided into 1-day and 30-day groups, each with control, water, saliva, blood, and lubricant oil contamination samples. Shear specimens were condensed in 4 × 4-mm anchor wells inundated with contaminant fluids before adding a ring mold with 3.5-mm-diameter central hole adapted immediately to the top for continued condensation under contaminant-submerged conditions. Compressive specimen samples were condensed while completely inundated by each contaminant using the American Dental Association Specification No. 1 amalgam mold apparatus. All specimens were tested with the Instron E3000 and E10000 at 0.5 mm/min, with data statistically evaluated using the Kruskal-Wallis procedure with IBM SPSS v25 and Wilcoxon signed ranks test.

Results: Shear test values (mean±SD) following intracapsular and extracapsular contamination after 30 days under 100% humidity at 37°C were as follows: control, 30.97±5.41 MPa; water, 30.63 ±4.41 MPa; saliva, 27.54 ±4.56 MPa; blood, 24.92 ±3.48 MPa; lubricant oil, 26.06 ±4.06 MPa. Compressive strengths (±SD) of similarly contaminated samples were as follows: control, 447.7 ±76.3 MPa; water, 343.6 ±70.1 MPa; saliva, 307.7 ±24.0 MPa; blood, 281.6 ±35.2 MPa; lubricant oil, 227.8 ±16.9 MPa.

Conclusions: Saliva, blood, and handpiece oil diminish compressive strength significantly, but water shows no statistically significant effect ($p>0.05$). Amalgam 30-day shear strength is significantly altered by contamination with water, blood, or handpiece lubricant oil ($p<0.05$). Remaining amalgam strength after extensive contamination may still be clinically

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functional relative to a previous ADA recommendation and when compared with resin-based direct restorative materials.

INTRODUCTION

Amalgam restorative material continues to provide a valuable service to dentistry, with over sixty per cent of US general dentists in a 2017 public health survey reporting the use of dental amalgam in their practice.[1]

Adequate compressive strength is essential for the success of an amalgam restoration and depends to a large degree on factors related to its metallic composition and handling.

The deleterious delayed expansion produced by moisture contamination in low copper zinc-containing amalgam was documented as early as the 1940s.[2-4] When uncontaminated, however, compressive strengths between zinc and non-zinc amalgam alloys were not significantly different.[5] Even when contaminated, zinc-free amalgams showed little or no delayed expansion[3-8] and no appreciable changes in compressive strength.[9]

K. W. Ray investigated the problem of amalgam contamination in 1941 and found that saliva, water, or salt solution incorporated into amalgams made from zinc alloys caused excessive growth and corrosion.[3] Significantly, he noted that the same was not true for amalgam specimens made from non-zinc alloys. Sweeney's laboratory confirmed this observation,[3] and results have been repeatedly confirmed by other investigators.[4,9,10] Data from a classic study by Phillips and others with non-zinc alloys showed no difference in strength at successive time intervals for up to 1 year, whether contaminated or uncontaminated (Table 1).[9]

Historically, when amalgam was triturated with a mortar and pestle, it was common to knead the fresh mass of amalgam in the palm of the bare hand prior to placement into the cavity preparation. This practice was well before mandatory use of rubber gloves, so perspiration from the skin became a contaminating source, estimated by the American Dental Association (ADA) to be equivalent to one drop of salt water.[2] Healey and Phillips in 1949 visually examined 1521 defective amalgam restorations in patients presenting to the Indiana University School of Dentistry operative dentistry clinic. They reported that, of the 1521 defective restorations they personally examined, 16.6% had resulted from delayed expansion.[11]

In all these published investigations, experimental conditions involved contamination that was introduced either before trituration or during palming of the amalgam. An exception was the study by Eames and others[6] that included contamination during condensation. His group condensed amalgam into 5 $\times$ 10-mm saliva-filled Teflon molds. Although saliva is the most common clinical contaminant, a literature search indicated that this 1973 study may be the only one looking at saliva itself as the contaminating source. A concise summary describing the experimental contamination methods of original investigators[2-7,9,10,12,13] is shown in Table 2.

Amalgam strengths prior to 1977 had been analyzed primarily using the diametral tensile test 15 minutes after mixing. In 1977, the ADA Council on Dental Materials and Devices replaced that test method with the one-hour compressive strength test, which was less technique sensitive and more reproducible.[14]

Since the introduction of dispersed-phase high-copper amalgam (HCA) alloys in the 1960s, studies confirmed beyond reasonable doubt that HCAs were not subject to dimensional changes resulting from fluid contamination.[6] In fact, more recently, the presence of zinc in HCAs has been reported as contributing to improved marginal integrity.[15,16]

Dental amalgam has widely received the reputation as a forgiving restorative material regarding its placement when contamination control is questionable. However, no reports were found that quantified the extent to which saturation with various contaminants, either prior to or during condensation, might affect the final strength of non-zinc ($<$0.04%) HCA.[12] Especially in managing clinical cases with less than ideal moisture control, it is useful for practitioners to understand the ranges of strength loss that might be expected should dental amalgam be maximally inundated with liquid contaminants (ie, totally uncontrolled) at placement.

The purpose of this laboratory study was to quantitatively differentiate the strength of water-, saliva-, blood-, and oil-contaminated amalgam samples from uncontaminated controls after 1 day and 30 days.

The null hypotheses for this study were that, relative to the control samples, there would be no statistically significant differences among the compressive or shear strengths of specimens prepared by condensing through various fluid contaminants for a high-copper dispersed-phase non-zinc dental amalgam.

Table 1: *Compressive Strengths of Non-zinc Versus Zinc-Type Amalgams: Thirty-day Compressive Strengths for Non-zinc Alloy in a Classic Study by Phillips and Others*[9]

Amalgam Types	Time Intervals		
	24 Hours	30 Days	60 Days
Non-zinc contaminated	312 (1%)	324 (−8%)	342 (1%)
Non-zinc control	311	351	338
Zinc contaminated	322 (−3%)	263 (−21%)	250 (−28%)
Zinc control	334	333	348

This table shows that zinc-containing amalgam contaminated with three drops of saline prior to condensation can be expected to lose roughly 20% of compressive strength stored at room temperature 30 days and nearly 30% after 60 days. Non-zinc alloys, however, showed no appreciable change in compressive strength at all for time intervals up to 12 months. Values in megapascals. N=6.

METHODS AND MATERIALS

This study involving 420 specimens was designed to assess the relative effects that various contaminants at placement may have on amalgam strength. A flow chart is provided in Figure 1.

Pre-encapsulated amalgam capsules (Valiant PhD-XT Sure-Cap, 800-mg alloy, 3-spill size, Ivoclar Vivadent, Inc, Amherst, NY, USA) were mixed using a triturator (Silamat S5, Manufacturer #002603, Vivadent ETS, Schaan FL, Austria) at 10 seconds per capsule, according to the manufacturer's instructions.

Pre-encapsulated amalgam was purchased directly from the manufacturer. Capsules had laser-sealed lids designed to be snapped off to release the amalgam contents after trituration.

After one drop of each contaminant was introduced inside the amalgam capsules, 40 × 9.4-mm pieces of electrical tape (Scotch Super 33+, Vinyl Electrical Tape, St Paul, MN, USA) were used to reseal the opened amalgam capsule lids with slight overlap of the ends and pressed tightly into the lid joint interface to assure no leakage of capsule contents during trituration. Control amalgam capsules (having no contaminant) in this group were also opened and then similarly resealed (Figures 2a through c).

A programmable timer with audible signal (model 06-662-51, Fisher Scientific, Traceable Calibration Control Company, Rochester, NY, USA) notified when set times had elapsed throughout this study.

Shear Strength Specimen Preparation

Anchor-well cylinders were poured with a mixture of orthodontic acrylic at a volumetric 2:1 powder:liquid ratio (polymethyl methacrylate diethyl phthalate polymer #003-07-0358, monomer #871-06-0719, Esschem Co, Linwood, PA, USA). One-inch (25-mm) diameter cylinders approximately 21 mm in height were prepared in a polyoxymethylene (Delrin) 15 hole specimen mold (Part #1599, Ultradent Products, Inc, South Jordan, UT, USA).

To serve as shear testing amalgam specimen condensation molds, fifteen 3.75 mm-thick Delrin disks were machined to 25 mm (1-inch) diameter with 3.5-mm-diameter centered holes, with each disk receiving a bisecting cut to produce two halves for easy removal from the molded specimen (Moran Innovations, Inc, Redlands, CA, USA).

Flat faces of the solid poured-resin cylinders were model-trimmed perpendicular to their outer walls. Holes to serve as cavity wells for the amalgam were drilled 4 mm deep in the center of the face, using a

Table 2: *Various Modes of Amalgam Contamination Reported in the Literature*

Investigators	Modes of Amalgam Contamination Used
ADA Commission 1941[3]	One drop of saturated NaCl solution was added to the alloy before amalgamation (trituration)
Sweeney 1941[4]	The mix of amalgam was mulled in the bare palm with the addition of one drop of a 0.9% solution of NaCl before condensation
Schoonover and others 1942[5]	One drop of salt water was placed in the capsule prior to trituration
Phillips and others 1954[9]	Mulled for 30 seconds in the palm of the hand with three drops of normal saline solution, prior to condensation
Zaazou, 1967[2]	Two drops of saline were added to the alloy and mercury inside the capsule prior to trituration
Eames and others 1973[6]	Specimens were packed into 5- × 10-mm saliva-filled Teflon molds
Fainsilber and others 1980[7]	20 μL 0.5% NaCl solution was added during trituration
Yamada and others 1981[11]	Amalgam was kneaded in the palm of the hand moistened with 2% saline solution for 20 seconds
Nelson and others 1990[12]	10 μL water was added to the sample during trituration, followed by two seconds of final trituration, which authors considered a "worst case scenario"
Osborne and others 1994[13]	10 μL water was added to the die after the first increment of alloy was placed, before condensation

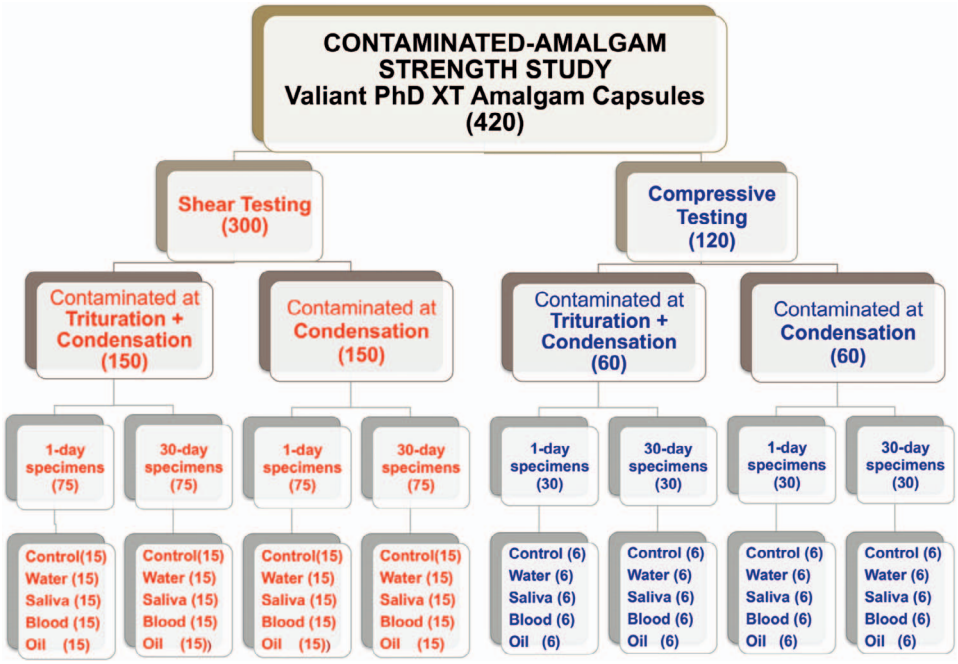


Figure 1. *Flow chart of overall research outline.*

machine lathe with a 4-mm (5/32-inch) diameter drill bit.

Each shear-testing sample group consisted of 15 poured-resin cylinders fully inserted into the 15 holes of the polytetrafluoroethylene molding tray, with 15 Delrin split-ring specimen forming molds (Moran Innovations) snugly seated into the recessed area of the same holes on top of the cylinders, adopted from a previous study testing shear strength of repaired amalgam.[17] Each inserted cylinder top surface was approximately 3-4 mm below the surface of the mold tray, providing space to seat each disk (Figure 3). This tray of specimens was clamped to a flat metal underplate 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 condenser. To standardize the condensation force, the carrier's spring tension was increased by bending it to a tighter curvature. This tension was calibrated on a digital balancing scale (Nexus NS-2000, Polyproducts Corp, Roseville, MN, USA) to a force of 1 lb (4.45 N). To standardize the condensation force, the carrier's spring tension force of 1 lb (16 oz) was measured at the point when the carrier sleeve was depressed.

A special nib was machined from stainless steel (Moran Innovations) to friction-fit over the large end of the amalgam carrier. This had a 1.5 mm-diameter (1.77-mm^2) nib 5 mm long, with a flat, non-serrated tip allowing for condensation of amalgam in the 3.75 mm-deep holes of the split-ring molds. The resulting pressure per condensation stroke with this tip was 2.52 MPa (4.45 N/1.77 mm^2). All shear-strength specimens throughout were condensed using this same calibrated condenser (Figure 4).

Each fresh amalgam mass was sectioned into four pieces using a sharp blade. Two of the quarters were used to fill the anchor-well in the acrylic cylinder below, and the remaining two filled the specimen-forming disk fitted on top.

Before any amalgam was introduced into the anchor well, the well was partially filled with the contaminant appropriate for that part of the study.

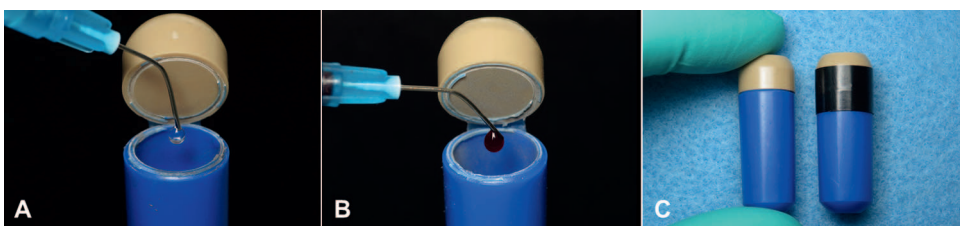
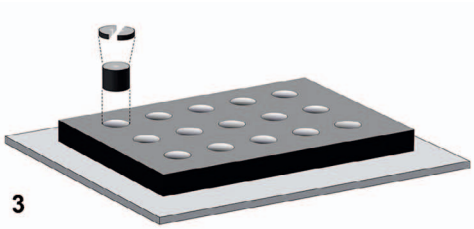
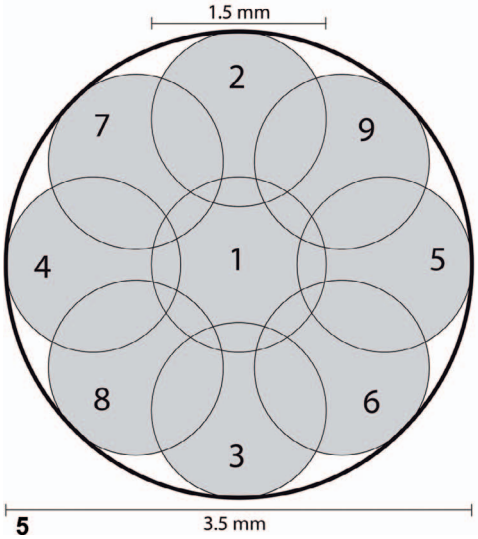


Figure 2. *(a and b) Drops of blood and saliva delivered to the trituration capsules. (c) After one drop of contaminant was placed, the capsule was resealed using vinyl electrical tape to avoid leakage during trituration.*





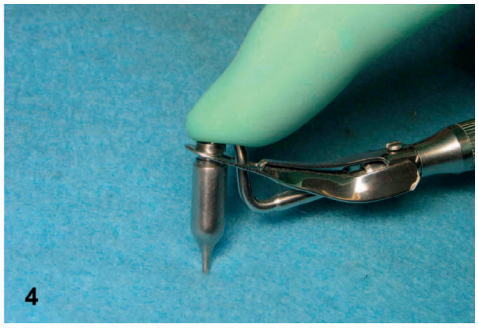


Figure 3. *Diagram of 15-hole mold tray assembly showing how split-ring top molds fit into the holes over the acrylic cylinder specimen anchor blocks.*

Figure 4. *Amalgam carrier modified as a condenser, depressed to the limit of 1 lb-force with custom 1.5 mm-diameter condensing nib attached.*

Figure 5. *Within the 3.5 mm-diameter specimen wells, the 1.5 mm-diameter condenser tip was placed once in the center and eight times around the perimeter to provide thorough condensation.*

Figure 6. *(a and b) Force-calibrated condensation of shear test amalgam through the central hole of the top split-ring specimen-forming disk inundated with saliva and with blood contaminants.*

It was subsequently loaded with the first amalgam increment and lightly directed into place using a 2.5 mm-diameter amalgam condenser (SS #1A, American Dental Mfg Co, Missoula, MT, USA) to approximately 1.5 mm below the top of the resin cylinder before condensing with the calibrated 1 lb-force instrument in a set pattern of nine strokes (Figure 5).

After assuring inundation with fluid contaminant, the next increment of amalgam was condensed in the same nine-stroke pattern using the 1 lb-force (0.45-kg) calibrated condenser. Layers of fluid contaminant were continually delivered to the amalgam surface to keep it flooded (Figure 6).

Sufficient extra amalgam was needed to produce a deliberate excess of mercury-rich layer on top, which was pressed down with a spreading or smearing action with less than 1 lb force using the polished flat handle of the cotton pliers to eliminate inadvertent voids. A razor blade at a low angle was used to shear off this soft minimum 1 mm-deep mercury-rich layer flush with the top of the acrylic cylinder. This surface was critical as the primary test plane between the anchor amalgam below and the form-molded cylindrical 3.5 mm-diameter test column or stub standing above.

Each acrylic resin cylindrical test block was transferred to one of the holes in the 15 hole resin-cylinder mold tray, where a split-ring Delrin disk was inserted and pressed tightly against the acrylic cylinder beneath it. These split-ring molds were a snug friction fit, being 1 inch in diameter, the same as the Ultradent mold holes. When secured into place, the central hole of the top mold was filled with fluid contaminant (either water, saliva, blood, or oil) to assure inundation of the fresh razor-cut amalgam surface located at the floor of this chamber. The central holes were slightly smaller in diameter (3.5 mm) than the anchor well (3.9 mm) to allow for complete contact of the amalgam to the anchor-well below in case of slight lateral eccentric discrepancy. It was vital that the contaminant material cover the entire critical surface.

One of the two smaller cut pieces of amalgam was lightly pushed into the split-ring central hole with the 2.5 mm diameter end of the amalgam condenser (amalgam condenser #1A, American Dental Mfg Co) with less than 1 lb-force. The amount of amalgam inserted was about 2 mm deep (approximately half the thickness of the 3.75 mm Delrin ring). After another layer of liquid contaminant inundated the surface, the nine-stroke pattern was used using the 1 lb-force calibrated condenser. The final amalgam

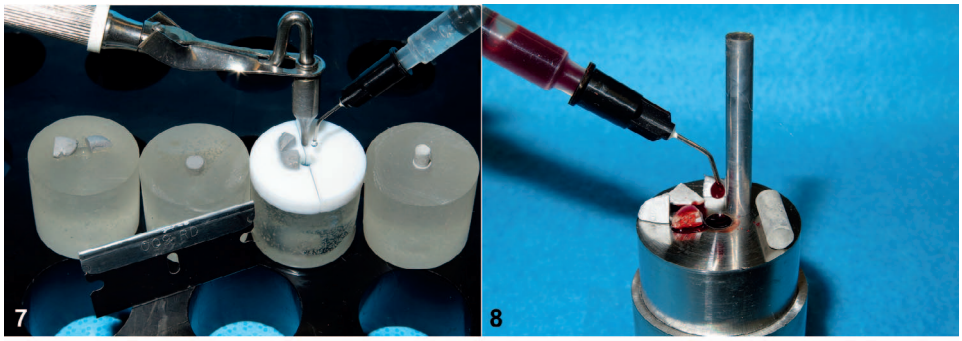


Figure 7. *Series of four resin anchor-wells demonstrating (a) two large quarters of fresh amalgam ready for condensation into the 4 × 4-mm anchor well preloaded with liquid contaminant, (b) condensed, overfilled, and razor-shaved specimen of fresh amalgam, (c) split-ring specimen-forming disc place in place with contaminant loaded first then the two smaller quarters of amalgam condensed while continuously submerged in liquid contaminant, and (d) the final shear-test specimen stub ready for testing at one day or one month.*

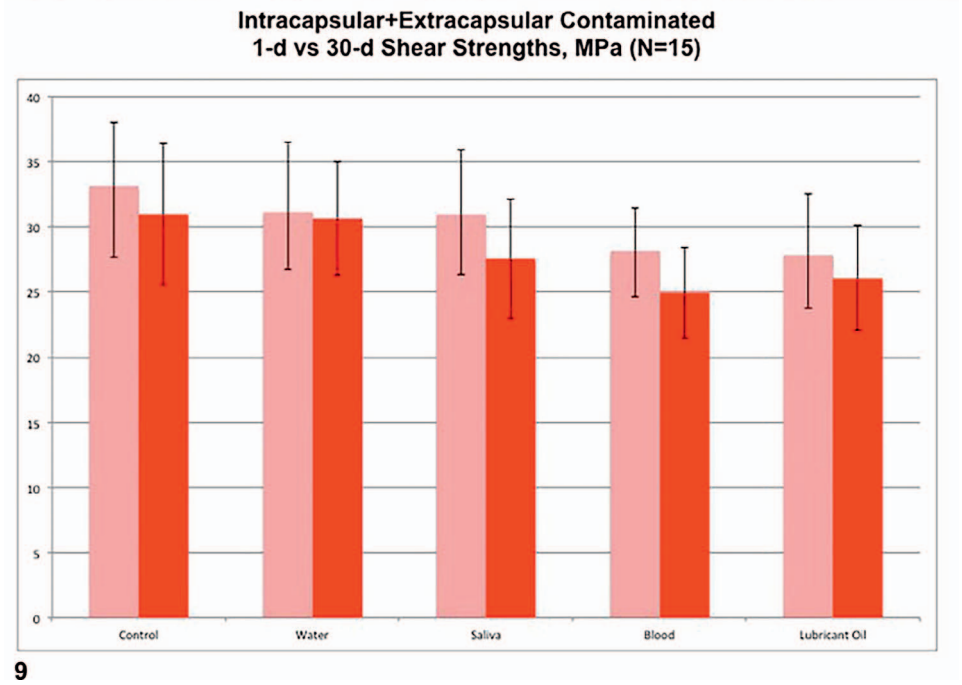


Figure 8. *ADA Specification No. 1 amalgam mold device showing quartered pieces of fresh amalgam ready to be inserted into the central chamber after blood was placed. More blood was added after each increment to keep the amalgam submerged below the blood surface. The piston plunger is standing ready to compress the contaminated amalgam through the central chamber with nearly 40 lb of weight. A final 4 × 9-mm pellet of condensed contaminated amalgam prepared for compression testing is shown lying on the top right of the mold device.*

Figure 9. *Shear strength mean values (MPa) at 1 day (light red) versus 30 days (dark red) following contamination at trituration (intracapsular) + during condensation (extracapsular). N=15.*

increment was similarly contaminant flooded and condensed, with excess amalgam swept away with a burnishing motion using the rounded angular bend of the condenser. The working time for specimens averaged 4.0 minutes ± 30 seconds. Figure 7 demonstrates the overall sequence to form the shear-testing specimens.

Fresh tubes of blood for this investigation were obtained from a hospital medical laboratory with donor identification undisclosed. Saliva was donated primarily by one of the investigators (BC). Water used in this study was deionized. Handpiece oil was Midwest Plus Handpiece Lubricant (part no. 380130, 2 fl oz [59 mL] RJR5, Dentsply Professional, Des Plaines, IL, USA).

All contaminant fluids were replenished with a minimum of five intervals per specimen at an estimated total of at least 0.25 mL to assure that each increment of amalgam was condensed under flooded or submerged conditions.

After a minimum of 2 hours, the 15 resin cylinders were individually pushed out of the Ultradent mold tray to remove their split-ring Delrin specimen-forming molds. Care was exercised not to disturb the standing fresh amalgam specimen stubs or columns. Samples for 24 hour testing were stored at 37°C under 100% humidity, and samples for 30 day testing were stored at 37°C under deionized water. Any inadvertent excess accumulation of amalgam at the base of the columns was carefully removed with a single-edged razor blade prior to testing.

Compressive Strength Specimen Preparation

The central well of the ADA Specification No. 1 amalgam compression-testing mold device was first loaded partway with the contaminant that was appropriate for each sample. Pre-encapsulated amalgam capsules were mixed using a triturator at 10 seconds per capsule according to the manufacturer's instructions. The resulting bolus of amalgam was

Table 3: *Shear Strength Test Results (MPa)*

Group	1-Day (±SD)	p Δ/C	30-Day (±SD)	p Δ/C	p Δ/1-d
Mean intracapsular+extracapsular contaminated amalgam shear strengths compared					
Control (C)	33.08±4.97)	—	30.97±5.41	—	0.032
Water	31.16±5.32	0.061	30.63±4.41	0.076	0.432
Saliva	30.89±5.02	0.539	27.54±4.56	0.202	0.001
Blood	28.12±3.25	0.002	24.92±3.48	0.040	0.038
Lubricant oil	27.82±4.73	0.006	26.06±4.06	0.042	0.198
Mean extracapsular-only contaminated amalgam shear strengths compared					
Control (C)	32.23±4.49	—	27.43±4.62	—	0.047
Water	29.03±5.29	0.164	31.46±3.75	0.015	0.334
Saliva	32.27±4.02	0.998	26.67±3.74	0.760	0.004
Blood	26.60±5.82	0.009	25.35±5.57	0.391	0.496
Lubricant oil	28.17±4.55	0.035	26.68±3.88	0.722	0.551

Sample means in megapascals; N=15. Abbreviations: p Δ/C, p *value of difference from the control mean; p Δ/1-d,* p *value of mean difference between 1-day and 30-day means.*

sectioned into quarters with a single-edged razor blade.

The initial increment of amalgam was directed into the central well or hole of the compression strength mold device and pushed into place through the fluid contaminant using the beaks of the cotton forceps. After assuring inundation with fluid contaminant, the next increment was added, until all four quarters of fresh amalgam were inserted. Layers of fluid contaminant were delivered by syringe to the surface to keep each increment of amalgam continuously covered. After all the amalgam was inside the device, the plunger rod was inserted and placed under compressive weight according to the ADA amalgam Specification No. 1 protocol[14] for compressive strength specimens (Figure 8). The resulting 4 mm-diameter × 9 ± 1 mm-long cylindrical specimens were carefully ejected from the mold device unaltered and stored in deionized water at 37°C until testing. The sample size of six was adopted from previous published compressive strength reports[9,18] and estimated to give 80% statistical power.

Instron Testing of Samples

Shear strength specimens were mounted into a jig (Moran Innovations), which positioned the specimen stubs horizontally to be tested at a 90° angle using an ElectroPuls E3000 Testing Machine (Instron North America, Norwood, MA, USA) with a semicircular notched blade and vertical crosshead speed of 0.5 mm/min. Values were recorded in megapascals.

Compressive strength specimens were tested standing vertically under compression in an ElectroPuls E10000 Testing Machine (Instron North America) with a crosshead speed of 0.5 mm/min and values similarly recorded in megapascals.

The null hypothesis was evaluated using the Kruskal-Wallis/Bonferroni procedure and tested at an α level of 0.05 with IBM SPSS v25 (Cary, NC, USA). The Kruskal-Wallis procedure, the nonparametric correlate of the one-way analysis of variance, was performed due to the smaller sample size and inability to verify assumptions of normality. The Wilcoxon signed ranks test was used to compare the 1-day and 30-day controls.

RESULTS

For intracapsular contamination specimens, the low weight of 0.13 g (<5% of total capsule weight) added by the black vinyl electrical sealing tape including weight of the one drop of contaminant fluid per capsule used in this study was considered not to have a significant effect on the results.

Shear Strengths

Mean shear strength reductions for 1-day samples contaminated both at trituration and during condensation (intracapsular+extracapsular) are shown in Table 3 and Figure 9. There was a consistent, although not statistically significant, reduction of strength by each group by 30 days.

One-day shear strength of the extracapsular saliva-contaminated sample (32.27 MPa) was equivalent to the control (32.23 MPa). This was repeated from a previous run yielding 33.6 MPa, apparently confirming this value.

Table 4: *Fracture Sites Examined Under Magnification*

Fx Sites	C1-E	W1-E	S1-E	B1-E	L1-E	C1-I	W1-I	S1-I	B1-I	L1-I	C30-E	W30-E	S30-E
Interface	1	1	0	5	2	0	0	0	1	0	3	1	2
Mixed	3	2	4	1	1	1	0	2	1	0	1	2	2
Bulk	11	12	11	9	12	14	15	13	13	15	11	14	11

These fracture sites were categorized as follows: interface, >3/4 intact surface; mixed, in between; bulk, <1/4 intact surface. Abbreviations: B, blood contaminated; C, control; E, extracapsular contamination (during condensation); I, intracapsular contamination (at trituration); L, lubricant oil contaminated; S, saliva contaminated; W, water contaminated; 1, 24 hours; 30, 30 days (month).

Thirty-day shear strength p values (p Δ/C) for the intracapsular+extracapsular sample group were water (p=0.076), saliva (p=0.202), blood (p=0.040), and lubricant oil (p=0.042), with the water-, blood-, and lubricant-contaminated groups rejecting the null hypothesis (Table 3).Among the shear strength samples, there was a general tendency for interfacial fractures (across the specific deliberate plane of contamination) in the saliva and blood samples (Table 4). Bulk fractures occurred more often than interfacial fractures, averaging 9 of 15 in saliva and blood extracapsular groups, and for saliva and blood intracapsular groups, the average was 13 of 15. Because this trend was similar throughout all samples, there may have been sufficient weakening from intracapsular contamination saturation at trituration that predisposed specimen fractures through the bulk rather than at the interface.

Any additional effect that intracapsular contamination had on shear strength occurred consistently regardless of contaminant source but not statistically significant (p=0.05, Table 3, Figure 10).

Compressive Strengths

Mean strengths for 1 day compressive samples contaminated both at trituration and during condensation were lower than the 1 day control but consistently increased after 30 days to the following: control, 447.7 ±76.3 MPa; water, 343.6 ±70.1 MPa; saliva, 307.7 ±24.0 MPa; blood, 281.6 ±35.2 MPa; lubricant oil, 227.8 ±16.9 MPa. The blood-contaminated amalgam value in the intracapsular+extracapsular group was diminished, 157.4 ±39.9, at 1 day but recovered significantly after 30 days (Table 5, Figure 11).

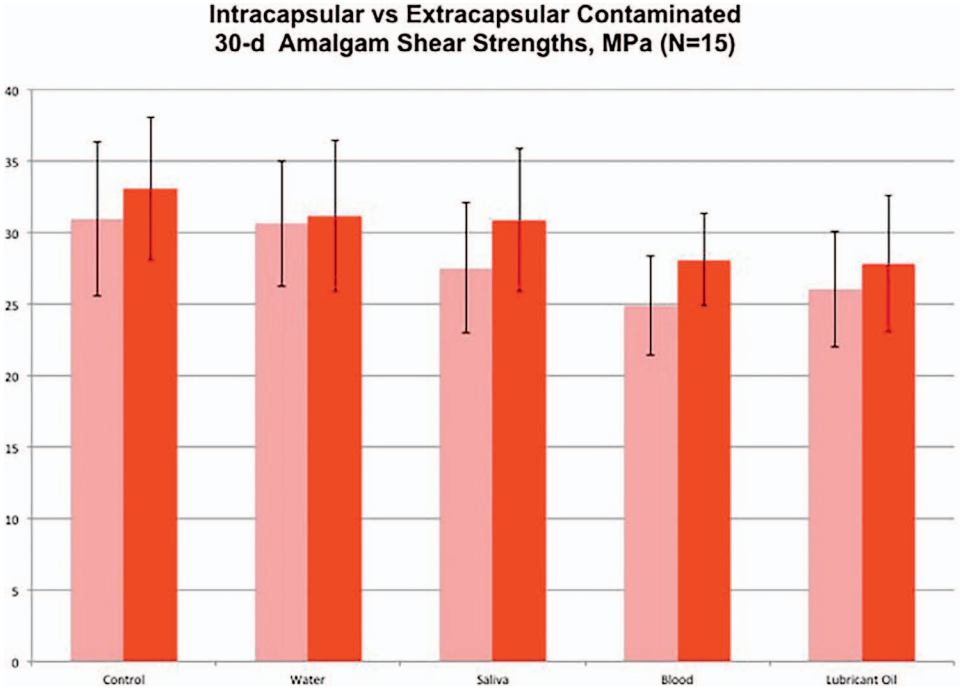


Figure 10. *Shear strength mean values (MPa) at 30 days following contamination at trituration (intracapsular+extracapsular, light red) + during condensation versus during condensation only (extracapsular, dark red). N=15.*

Table 4: *Fracture Sites Examined Under Magnification (ext.)*

Fx Sites	B30-E	L30-E	C30-I	W30-I	S30-I	B30-I	L30-I
Interface	2	0	0	0	0	1	0
Mixed	3	1	0	0	2	1	1
Bulk	10	14	15	15	13	13	14

Compressive strength values below the selected minimum of 241 MPa, corresponding to the ADA-suggested minimum of 35,000 psi,[9] were primarily in the 1 day (blood, 157.4 ±39.9 MPa; lubrication oil, 188.4 ±52.5 MPa) samples. At 30 days, only the lubricant oil (227.8 ±16.9 MPa) fell below this hypothetical level (Table 5, Figures 11 and 12).

Compressive Strength Results Relative to Contaminants

Water-contaminated samples complied with the null hypothesis, whereas other contaminated samples were rejected ($p>0.05$).

After 30 days, only lubricant oil, when permeated throughout the amalgam mass by both trituration and during condensation, had strength at or below the suggested minimum standard of strength (Table 5, Figure 12).

Compressive Strength Results Relative to Shear

In general, all sample mean intracapsular+extracapsular compressive strengths increased between 1 day and 30 days (Table 5, Figure 11). The converse was found for shear strengths with all intracapsular+extracapsular samples diminishing in value but not to a statistically significant extent (Table 3, Figure 9).

Intracapsular Contamination (at Trituration) Results Relative to Extracapsular Contamination (During Condensation)

As a means of introducing contamination, placing a drop inside the amalgam capsule prior to trituration was potentially more thorough than flooding during condensation alone. This was the method chosen by many amalgam investigators (Table 2), and, especially for compressive strengths, its detrimental effect was slightly enhanced beyond extracapsular contamination alone. This effect was dramatized more in the 1 day than in the 30 day amalgam samples. For example, MPa strengths in the saliva contamination group were reduced from 313.2 ± 38.9 to 252.1 ± 31.7 at 1 day and from 326.7 ± 65.9 to 307.7 ± 24.0 at 30 days. In keeping with worst case scenario prospects, long-term conclusions in the present study have been based on intracapsular+extracapsular contamination with 30 day compressive strength results.

DISCUSSION

Dental amalgam has gained the reputation as a relatively safe restorative material to use in situations where isolation against moisture contamination is compromised. Taking it to an extreme, this study attempted to answer what the worst effect on the final strength of amalgam might be, ascertained from overt contamination by total inundation of amalgam during placement. Individual specimens needed to be prepared in a strictly uniform manner

Table 5: *Compressive Strength Test Results (MPa)*

Group	1-Day (±SD)	p Δ/C	30-Day (±SD)	p Δ/C	p Δ/1-d
Mean intracapsular+extracapsular contaminated amalgam compressive strengths compared					
Control	414.3±85.3	—	447.7±76.3	—	0.530
Water	301.2±22.6	0.099	343.6±70.1	0.187	0.028
Saliva	252.1±31.7	0.017	307.7±24.0	0.006	0.084
Blood	157.4±39.9[a]	<0.001	281.6±35.2	0.001	0.182
Lubricant oil	188.4±52.5[a]	<0.001	227.8±16.9[a]	<0.001	0.875
Extracapsular-only contaminated amalgam compressive strengths compared					
Control	430.5±36.1	—	441.3±67.9	—	0.463
Water	368.1±43.1	0.251	402.2±36.4	0.577	0.028
Saliva	313.2±38.8	0.017	326.7±65.9	0.045	0.917
Blood	273.3±41.8	0.008	247.5±103.2	0.026	0.753
Lubricant oil	260.6±29.5	0.002	216.7±23.8[a]	0.002	0.116

Sample means in megapascals; N=6.
[a] Mean values are less than 35,000 psi (241 MPa) ADA-suggested[9] minimum strength.

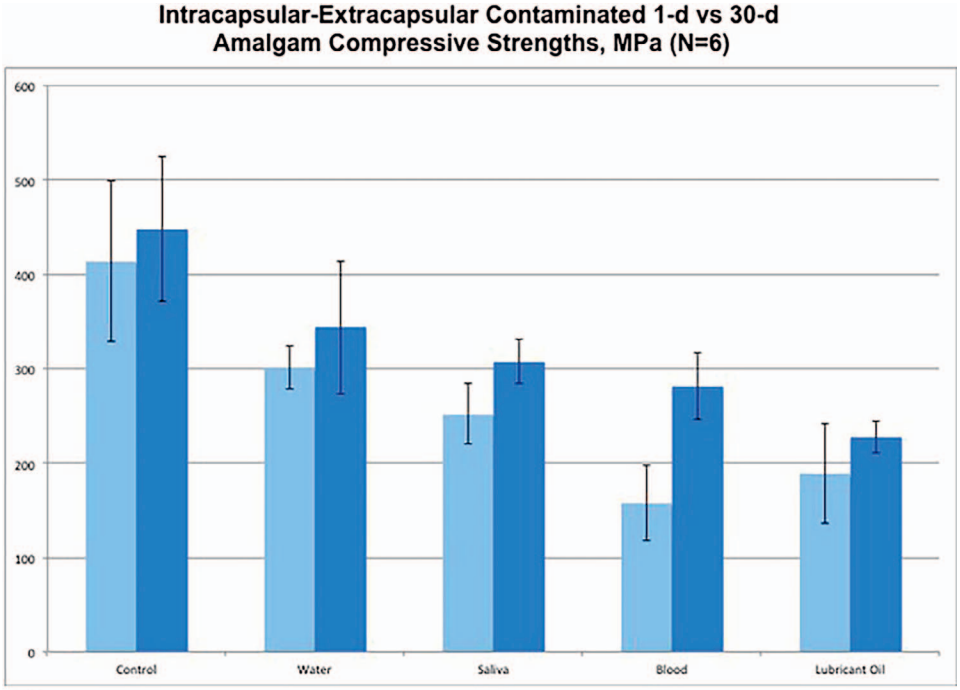


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Figure 11. *Compressive strength mean values (MPa) at 1 day (light blue) versus 30 days (dark blue) following contamination at trituration (intracapsular) + during condensation (extracapsular). N=6.*

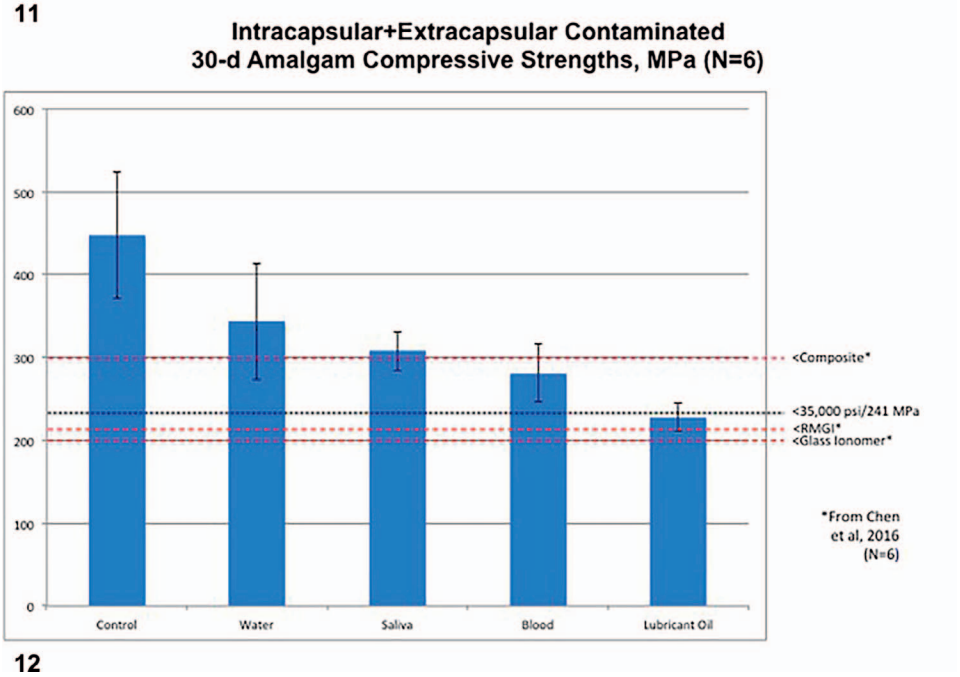

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Figure 12. *Compressive strength mean values (MPa) at 30 days following contamination at trituration (intracapsular) + during condensation (extracapsular). Bar graph display of variously contaminated amalgam strengths, with dashed lines indicating intact uncontaminated strengths of a posterior composite resin material (Quixfil, Dentsply Sirona), typical resin-modified glass ionomer (RMGI; Fuji II, GC America), and conventional glass ionomer (GI; Fuji IX, GC America) compressive strengths from Chen and others.[19] The line at 35,000 psi (241 MPa) indicates the suggested minimum compressive strength recommended historically by the ADA for amalgam.[9] N=6.*

to limit the manipulative variables affecting the compressive and shear strengths.

The protocol required regular and thorough condensation, complete inundation of amalgam during condensation that would not interfere with consistent quality of condensation, and a system of parallel analysis (shear testing) as a side reference to the traditional method of compressive testing.

Of particular interest was the relative reduction in strength resulting from potential chairside contaminants when introduced overwhelmingly during amalgam condensation. It was also of interest to investigate changes induced after 30 days by contamination at the trituration stage where distribution would be total and homogeneous and between aqueous-based and oil-based contaminants.

Contaminants generally recognized as a potential threat to ideal amalgam placement were selected: water, saliva, blood, and oil. Handpiece lubricant oil was included in this study because it is considered a potential source of contamination from handpiece spray. It was useful to learn if such a nonaqueous contaminant might degrade amalgam strength beyond that produced by water-soluble contaminants. Despite thorough contamination by handpiece lubrication oil agents prior to and during amalgam condensation, at 30 days the retained compressive strength was nearly 50%.

Valiant PhD-XT is a non-zinc, high-copper, phase-dispersed alloy admixture. Each Sure-Cap capsule contained 800 mg alloy and 746 mg Hg, with a slower setting time (XT indicates extended time). The working time for specimens in all groups of the present study averaged 4.0 minutes ± 30 seconds, which was within the manufacturer's stated working time of seven minutes.

The condensation force of 1 lb (0.45 kg) with a 1.5 mm-diameter flat nib was determined empirically to be optimal because greater force than this resulted in greater penetration through the amalgam than actual compaction.

The 24 hour compressive strength of Valiant PhD was rated by the manufacturer at approximately 75,000 psi (517 MPa).

What Is the Critical Level of Weakness Relative to Clinical Acceptability?

Compared with other restorative materials such as composite resin or direct gold, amalgam strength is purportedly superior when contaminating conditions cannot be totally controlled. Literature sources, however, were indecisive about what an actual critical threshold of clinical acceptability should be. ADA Specification No. 1 stated only a minimum of 80 MPa tested one hour following ejection from the dental amalgam specimen mold.[14]

ADA Specification No. 1 historically had required a minimum compressive strength of 35,000 psi (241 MPa) at 24 hours.[9] Less strength was conjectured to increase the possibility of fracture under normal biting stress. For durability of the material to resist normally expected clinical biting loads, the degree loss of amalgam strength is not considered as important as maintaining strength above the suggested minimum.[9]

It is not known specifically what the desired minimum strength needs to be for amalgam. When there is adequate bulk, such as in restorations with deeper and wider preparation designs, the inherent alloy strength does not need to be as great.[18] The minimum limit would also vary according to other factors such as stress locations involving central compressive versus edgewise shearing forces.

The period of time when the amalgam is setting is most critical; it has been estimated that 85% of the strength is attained by eight hours after placement.[18] Strength often increases slightly after 24 hours, which has been associated with continued chemical reactions. Phillips suggested that equilibrium of amalgam in the mouth is reached only after an indefinite period of time, if ever.[18]

Compressive Strength Results Relative to Other Dental Materials

The Instron E3000 load cell used for amalgam shear strength testing was inadequate for compressive testing, which instead required use of the Instron E10000.

It is useful to compare these values with the normal compressive strength of other resin-based restorative products that might have substituted for amalgam. Compressive strength values of the control and water-, saliva-, and blood-contaminated groups after 30 days was still greater than a typical resin-modified glass ionomer (RMGI) manufacturer's[19] stated value of 230-274 MPa (for Fuji II LC, GC America, Alsip, IL, USA) and that was "indicated for stress-bearing Class II restorations." Mean contaminated amalgam values were also considerably greater than the 178 MPa for a conventional glass ionomer (GI; Fuji IX, GC America, Alsip, IL, USA) restorative material.[20]

The mean compressive strength of amalgam 30 days after maximum contamination by saliva, which is the chief contaminant under oral conditions, was 326 ± 65.9 MPa. This value was roughly equivalent to the 200 to 340 MPa textbook range for compressive strength of microhybrid composite and 230-290 MPa for microfilled composite.[21]

Comparable to the present study, a laboratory report by Chen and others[22] with a conventional glass ionomer (Fuji IX), a resin-modified glass ionomer (Fuji II LC), and a posterior composite resin (Quixfil, Dentsply Sirona, York, PA, USA) showed compressive strengths of 203, 217, and 300 MPa, respectively. These results[22] are particularly relevant in that the GI, RMGI, and posterior composite samples were incubated underwater for 30 days and tested similar to the present protocol (Figure 12).

The 30 day mean compressive strengths of water- and saliva-contaminated amalgam in the present study exceeded the reported values for uncontaminated posterior composite, RMGI, and GI in their study. Also, the blood- and oil-contaminated amalgam strengths were greater than their RMGI and GI values (Figure 12). It should be noted that in actual practice, contamination with either blood or handpiece oil would be highly improbable during the condensation of amalgam.

The maximally contaminated saliva sample after 30 days still retained a compressive strength above the suggested ADA minimum recommendation for amalgam.[9]

Why Test for Shear Strength in Addition to Compressive Strength?

Compressive force, which assesses the overall bulk of amalgam, is the standard method of evaluating amalgam strength. Amalgam, however, can be subject more to tensile than to compressive failure under certain clinical stress conditions. For this reason, shear strength testing was included.

From a previous study, a method of continuously condensing a column of amalgam[17] was adopted to assure not only complete submersion of the amalgam as it was being condensed but also that the contaminating agent was applied directly at the shear-force interface to avoid question whether the actual testing surface had been contaminated. This was considered by the authors to be more specifically focused than other traditional ISO testing methods for estimation of amalgam shear strength under "worst case scenario" conditions, as Nelson and Mahler[12] had described.

The significance of the present study design was that shear testing occurred perpendicular to the discrete plane of known contamination. Although the amalgam had already been condensed while totally submerged in fluid contaminants in addition to contamination at trituration, specific contamination at that particular interface is considered the most crucial. If the inherent interface joint strength was great enough not to cleave at that plane, the amalgam would fracture more angularly into the bulk. In this way, shearing action became a direct test of weakness induced by the contaminant at what might be considered the most vulnerable location.

However, seldom did the fracture occur at the interface. This may indicate that the patterned condensation with the 1.5 mm-diameter 1 lb-force condenser on the plane of specifically known contamination allowed the added increments of amalgam to join effectively despite interference from the contaminants.

Amalgam shear strength after placement was degraded during the following 30 days under water at 37°C.

Compressive forces consist of a component of tensile stress in expansion.[23,24] The compressive test results in the present study were more definitive than the shear strength results. However, in actual clinical cases, it is less frequent that amalgam fails by direct perpendicular compressive force alone. Amalgam failures are generally noted from tensile or shear action in relatively unsupported areas such as in isthmus fractures.[18] In this regard, shear-testing data are considered relevant.

Possible Mechanism of Action for Amalgam Contamination Resistance

Mercury is a metal that uniquely exists in a liquid state at ambient temperature. This molten state allows small particles of other metals to combine and solidify to form an amalgam. The ability of amalgam to flow together and join with itself in a coherent mass owes to the capacity of the mercury to unite with other increments of liquid mercury in the mixture around and through the contaminating fluid. As mercury components coalesce under condensation forces, non-mercuric liquids are apparently expressed outside the amalgam mass. It is postulated that proteinaceous elements of blood and saliva may cling to particles of amalgam alloy and are not as readily expelled. The compressive specimens that had been contaminated with saliva and blood were approximately 0.5-1.0 mm longer than control or water- or oil-contaminated specimens. This was assumed to be due to the residual incorporation of mucin and formed blood elements within the mass, which were unable to be fully squeezed out under condensation pressure.

There may be properties of handpiece oil that likewise have an affinity for solid metallic particles. It is speculated that this factor could cause inhibition of significant chemical actions that ordinarily would have occurred and prevented strengthening of the amalgam during the 30-day incubation storage period.

The remaining amalgam strength of 35,000 psi at 30 days as a suggested minimum value, based on a past ADA recommendation for minimum acceptability,[9] may still be considered reasonably functional.

Mean compressive values for the water-, saliva- and blood-contaminated samples, in the group

including both intracapsular and extracapsular contamination, indicated amalgam strength after 30 days to be at least comparable to published values for intact RMGI. Mean values individually for water-, saliva-, blood-, and oil-contaminated samples after 30 days were superior to the published value[17] of intact uncontaminated GI cement (Figure 12 shows 30-day compressive strengths).

Power and sample size analysis conducted from a prior pilot study anticipated a larger effect size. For data in which the null hypothesis was retained, no post hoc power analysis was conducted.

It is recognized that final conclusions about amalgam strength cannot be determined solely by compressive and shear testing. However, although salivary contamination is recognized as the main challenge clinically, thoroughly condensed amalgam may be capable of providing a functional restoration, even if overwhelmingly challenged by water, saliva, blood, or lubricating oil contaminants.

To conduct studies on actual patients with the amalgam placed totally under these contaminating factors would likely be considered unethical. The closest viable alternative is laboratory testing, from which results the clinician should be able to prognosticate a certain range of outcomes and judge their practicality.

Testing of alternative resin-based restorative products for comparison with an amalgam alloy was desired but not considered feasible due to inherent limitations of the materials. Otherwise, future studies might include testing whether direct gold, glass ionomer, or composite resins can sustain similar contamination without undue debilitation of strength and integrity.

It would be of interest to study whether use of an automatic mechanical condensing device instead of hand condensation would provide greater amalgam strength results under similar conditions. Also, amalgam tensile type testing could be accomplished using both a lower and an upper split-ring mold design to produce specimens for analysis in a three-point stress test, directed across planes of deliberately induced contamination.

CONCLUSIONS

- Under conditions of this study, contaminants reduce amalgam 30-day compressive strength in increasing order: water, saliva, blood, and handpiece lubricant oil.
- Of the water, saliva, blood, and handpiece lubricant oil contaminants tested, only water complies with the null hypothesis having no significant effect on amalgam compressive strength ($p>0.05$).
- Despite thorough contamination of amalgam by water, saliva, blood, or handpiece lubricant oil contamination agents, prior to and during condensation, the greatest mean reduction in compressive strength at 30 days is 44% by blood and 51% by the oil.
- Amalgam 30-day mean shear strength is significantly altered by contamination with water, blood, or handpiece lubricant oil ($p<0.05$).
- With total contamination at placement, mean amalgam compressive strength after 30 days is comparable with uncontaminated composite resin and resin-modified glass ionomer and substantially greater than uncontaminated glass ionomer under similar reported laboratory conditions.

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Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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