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Design and evaluation of a filter-based chairside amalgam separation system

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ABSTRACT

This study evaluated the ability of a chairside filtration system to remove particulate-based mercury (Hg) from dental-unit wastewater. Prototypes of the chairside filtration system were designed and fabricated using reusable filter chambers with disposable filter elements. The system was installed in five dental operatories utilizing filter elements with nominal pore sizes of 50µm, 15µm, 1µm, 0.5µm, or with no system installed (control). Daily chairside wastewater samples were collected on ten consecutive days from each room and brought to the laboratory for processing. After processing the wastewater samples, Hg concentrations were determined with cold vapor atomic absorption spectrometry (USEPA method 7470A). Filter systems were exchanged after ten samples were collected so that all five of the configurations were evaluated in each room (with assignment order balanced by a Latin Square). The numbers of surfaces of amalgam placed and removed per day were tracked in each room. In part two, new filter systems with the 0.5µm filter elements were installed in the five dental operatories and vacuum levels at the high-velocity evacuation cannula tip were measured with a vacuum gauge. In part three of the study, the chairside filtration system utilizing 0.5µm and 15µm filter elements was evaluated utilizing the ISO 11143 testing protocol, a laboratory test of amalgam separator efficiency utilizing amalgam samples of known particle size distribution. Mean Hg per chair per day (no filter installed) was 1087.38mg (SD = 993.92mg). Mean Hg per chair per day for the 50µm, 15µm, 1µm, 0.5µm filter configurations was 79.13mg (SD = 71.40mg), 23.55mg (SD = 23.25mg), 17.68mg (SD = 17.35mg), and 4.25mg (SD = 6.35mg), respectively (n = 50 for all groups). Calculated removal efficiencies from the clinical samples were 92.7%, 97.8%, 98.4%, and 99.6%, respectively. ANCOVA on data from the four filter groups, with amalgam-surfaces-removed included as a significant covariate, was statistically significant ($P < 0.0001$). Tukey post-hoc comparisons ($P \leq 0.05$) indicated that the 50µm filter removed less mercury than all other filters and the 0.5µm removed more mercury than the 50µm and 15µm filters. Chairside vacuum measured on chairs with the 0.5µm filters installed were minimally affected at the time of installation, and then gradually diminished as the filters became loaded with debris. The 0.5µm configuration passed the ISO 11143 testing protocol at 96.8% efficiency.

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1. Introduction

The anthropogenic release of mercury (Hg) into the environment has become a concern due to an increase in the number of fish consumption advisories (USEPA, 2001). One long-term study suggests that prenatal exposure to methyl Hg from the consumption of Hg-contaminated fish can produce neurobehavioral abnormalities in children (Grandjean et al., 1999). In addition, the promulgation of new sampling (USEPA, 1996) and analytical methods with lower detection limits (USEPA, 2002) has made possible the dramatic lowering of Hg discharge permit levels for wastewater treatment plants (WWTPs).

To reduce the Hg released into wastewater treatment systems, U.S. environmental regulators can enforce discharge limits on users of WWTPs (Stone et al., 1999). Environmental regulators have required dental clinics to use both Best Management Practices (BMPs, office procedures to limit the release of Hg-containing wastes) and amalgam separators [Connecticut, 2006; Maine, 2003; Massachusetts, 2006; New Hampshire, 2005; New York, 2003; Oregon, 2008; Palo Alto, California, 2005; Rhode Island, (Narragansett Bay Commission), 2004; Vermont, 2005; Washington, 2006; Wichita, Kansas, 2000]. The American Dental Association (ADA) has recently added amalgam separators to its Best Management Practices for Amalgam Waste (ADA, 2007).

An assortment of amalgam separation equipment is available in the marketplace with wide ranges in both cost and complexity (Fan et al., 2002; Batchu et al., 2006a; Hylander et al., 2006). This study evaluated the efficacy of a low-cost chairside filtration system to remove Hg in the form of amalgam particulate from dental-unit wastewater. Low-cost chairside filters may be an attractive alternative to more costly amalgam separators, or can lengthen the lifetimes of more complex centrally located pretreatment systems if used as a pre-filter. We hypothesized that low-cost filtration systems installed at the dental chair can remove substantial amounts of Hg-containing particulate without impacting the quality of chairside vacuum levels.

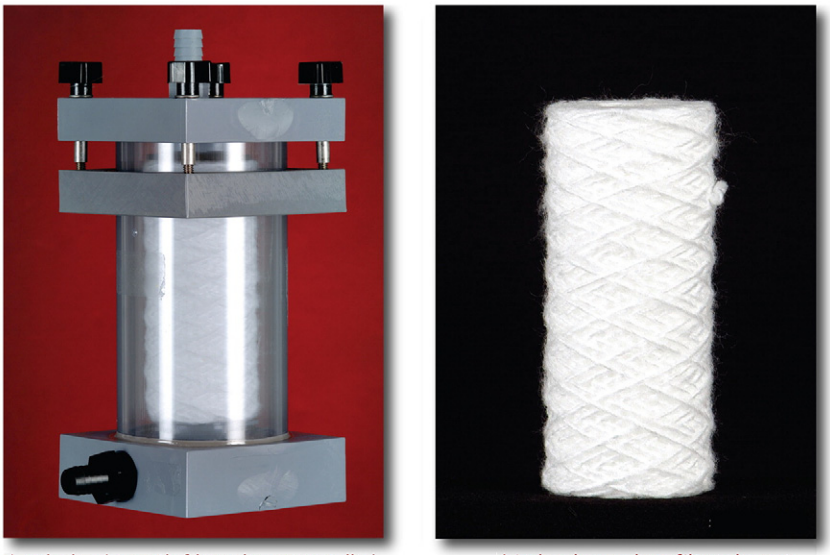
2. Materials and methods

This study was carried out in three parts.

2.1. *Clinical evaluation of chairside filtration system (Hg mass levels)*

The filtration system was fabricated with a reusable chamber and replaceable filtration elements designed to be installed chairside (Fig. 1). Filtration systems with nominal filter pore sizes of 50μm, 15μm, 1μm, or 0.5μm, or with no filter (control), were installed in five dental operatories. Daily chairside wastewater samples (total daily wastewater production from each chair) were collected from each room in air/water separators (Fig. 2), immediately downstream from the filters, on ten consecutive days. Filter systems were exchanged after ten samples were collected so that all five of the configurations were evaluated in each room. The assignment of filter system to dental operatory was order balanced by a Latin Square experimental design. New vacuum hoses and fittings were installed when each new filter system was placed. Each dentist tracked and recorded the number of amalgam-surfaces placed and removed in each operatory. Wastewater samples and forms recording amalgam-surfaces-placed and amalgam-surfaces-removed were collected at the end of each day.

All dental chairs used in this study were equipped with standard chairside traps (Parts Warehouse, Inc., Lynden, Washington USA) located upstream from the filter system and the air/water separator. The chairside traps used have round pores with a mean maximum diameter of 936μm and a



6 inch chamber with filter element installed   6 inch polypropylene filter element

Fig. 1 – Photographs of the filter chamber (left) and filter element (right) used in this study. The chamber is reusable, while the filter element is disposable and should be collected for recycling. (Photographs were taken by HM1 Dwayne R. Snader, Naval Health Clinic, Great Lakes, Illinois, USA).

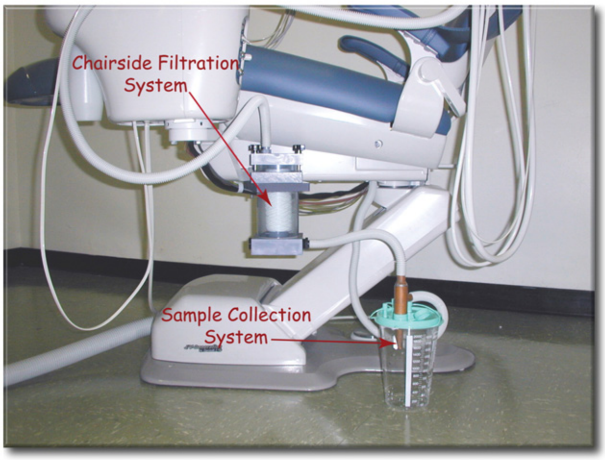


Fig. 2 – Photograph of the filtration and sample collection systems installed on a dental chair. Daily wastewater samples were collected after the wastewater passed through the filter. The sample collection system is used only for collecting wastewater samples for analysis.

roundness value of 1.37. New chairside traps were placed daily, prior to the start of wastewater collection.

In the laboratory, chairside wastewater samples (total daily wastewater production from each chair) were filtered utilizing 0.45μm pore size mixed cellulose ester membrane filters (Toyo Roshi Kaisha, Ltd, Japan; Lot # 60324200) with positive pressure (argon gas). After filtering each chairside wastewater sample, the membrane filters (with residual debris) were placed into two-liter borosilicate glass beakers with borosilicate glass covers and digested in 200ml of *aqua regia* (3 volumes of concentrated HCL to 1 volume of concentrated HNO_3) at 95°C for 120min. Each sample was cooled to room temperature, transferred to a one-liter borosilicate glass volumetric flask, (which had previously been acid washed) and diluted to the one-liter mark with double deionized water. Two 100-ml aliquots from each volumetric flask were stored in high-density polyethylene sample containers at 4°C until analyzed for total Hg by U.S. Environmental Protection Agency (USEPA) method 7470A (cold vapor atomic absorption spectrometry) (USEPA, 1994). All samples were analyzed within 28 days of processing. The instrument used to analyze the digested samples was a Varian Model 600 atomic absorption spectrometer (Varian Analytical Instruments, Palo Alto, California, USA). Quality Assurance/Quality Control procedures with duplicates and spiked samples were completed as required by USEPA Method 7470A. Total Hg in units of mg Hg per chair per day was calculated from the mean of the two 100-ml aliquots analyzed.

2.2. *Effect of filter systems on chairside vacuum levels*

After completing the first phase of the study, the filtration systems were removed from the dental chairs and baseline vacuum levels were measured with calibrated Flowcheck™ instruments, Fig. 3 (RAMVAC, Inc., Spearfish, South Dakota, USA). The Flowcheck™ vacuum gauge has a vendor-claimed accuracy of ± 2.5%. Values were recorded in units of inches of Hg and converted into kilopascals (kPa). Five new filter chambers with new 0.5μm filter elements, vacuum lines, and fittings were installed on the dental chairs and vacuum levels were measured at time '0' (immediately after placement of the filters), and after one, two, three, four, five, six, seven and eight weeks. All vacuum measurements were taken in triplicate and averaged.

2.3. *ISO 11143 testing of chairside filtration systems*

The ISO 11143 protocol (ISO, 1999) is a laboratory test designed to evaluate the efficiency of amalgam separators utilizing a 10.00g amalgam sample with a known particle size distribution: 6.00g of particles with diameters between 0.5mm and 3.15mm, 1.00g with diameters between 0.1mm and 0.5mm, and 3.00g with diameters less than 0.1mm. Chairside filter chambers with 0.5μm and 15μm filter elements were tested using the ISO 11143 protocol. Amalgam samples were obtained from Becker Messtechnik, GmbH (Eschborn, Germany). Efficiencies were calculated by determining the mass of the amalgam sample that passed through the separator and collected on a series of three membrane filters with pore sizes of 12μm, 3μm and 1.2μm. Each separator was tested six times (three empty and three fully loaded) at a flow rate of 0.5l/min. The lower value of the efficiency calculated from the two test series (empty separator and full separator) is the reported efficiency of the separator. To pass the ISO 11143 protocol, the separator efficiency must be at least 95% (mass fraction).

3. Results

3.1. *Part 1: Hg mass levels*

The mean Hg level (in units of mg Hg per chair per day) with no filtration system installed on the dental chair (baseline data)

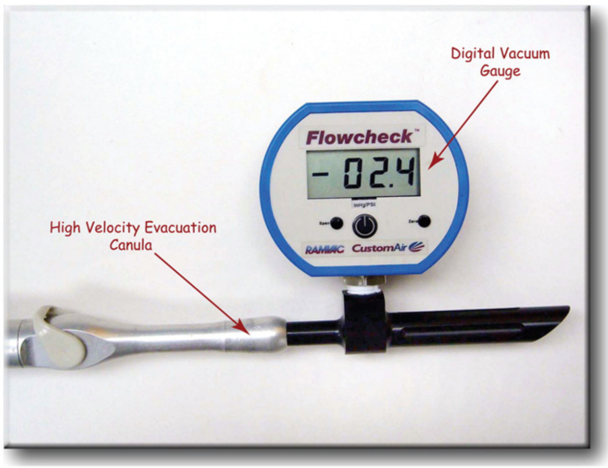


Fig. 3 – Photograph of the instrument used to measure chairside vacuum levels. The instrument reads in units of "inches of Hg" and values were converted into kilopascals (kPa). The Flowcheck™ vacuum gauge has a vendor-claimed accuracy of ±2.5%. The 2.4 in. of Hg pictured in the photograph corresponds to 8.1 kPa.

Table 1 – Mean Hg levels (mg Hg per chair per day) for the different test groups

Group	Mean Hg/chair/day (mg)	Homogeneous subsets (Tukey, $P \leq 0.5$)
Baseline (no filter installed)	1087.38 mg (n=50, SD=993.92 mg)	–
50 μm cartridge filter	79.13 mg (n=50, SD=71.40 mg)	A
15 μm cartridge filter	23.55 mg (n=50, SD=23.25 mg)	B
1 μm cartridge filter	17.68 mg (n=50, SD=17.35 mg)	B, C
0.5 μm cartridge filter	4.25 mg (n=50, SD=6.35 mg)	C

Post hoc testing data (Tukey, $P \leq 0.05$) are presented in the third column. Fifty samples were obtained from each of five different dental treatment rooms for a total of 250 samples.

was found to be 1087.38mg (n = 50, SD = 993.92mg). The means for the samples from the 50μm, 15μm, 1μm, 0.5μm filter systems were 79.13mg (n = 50, SD = 71.40mg), 23.55mg (n = 50, SD = 23.25mg), 17.68mg (n = 50, SD = 17.35mg), and 4.25mg (n = 50, SD = 6.35mg) Hg per chair per day, respectively. This data is summarized in Table 1. Calculated clinical removal efficiencies (using the mean baseline measurement as the denominator) for the 50μm, 15μm, 1μm, 0.5μm filter systems were 92.7%, 97.8%, 98.4%, and 99.6%, respectively, and are presented in Table 2. When amalgam-surfaces-removed is included as a significant covariate, ANCOVA on data from the four filter groups was statistically significant ($P < 0.0001$). Tukey post-hoc comparisons ($P \leq 0.5$) indicated that the 50μm filter removed less mercury than all other filters and the 0.5μm removed more mercury than the 50μm and 15μm filters (Table 1).

The mean numbers of amalgam-surfaces placed and removed per day were 19.11 (n = 250, SD = 12.31 surfaces) and 1.28 (n = 250, SD = 2.18 surfaces), respectively. A total of 826 patients were seen during the course of this study with 4777 surfaces of amalgam placed and 319 surfaces of amalgam removed. Of the clinical variables tracked (amalgam-surfaces-placed, amalgam-surfaces-removed, and treatment room), only the number of amalgam-surfaces-removed was found to be a significant covariate.

3.2. *Part 2: vacuum levels*

Chairside vacuum level data are presented in Table 3. Baseline vacuum levels (no filter installed) in kilopascals (kPa) averaged 7.2kPa (n = 5, SD = 0.7kPa). After initial filter placement mean vacuum levels were 6.6kPa (n = 5, SD = 0.4kPa), a decrease of 0.6kPa. After the first week mean vacuum levels were 6.4kPa (n = 5, SD = 0.4kPa). After weeks two, three, four and five mean vacuum levels were 6.1kPa (n = 5, SD = 0.7kPa), 6.4kPa (n = 5, SD = 0.5kPa), 5.8kPa (n = 5, SD = 1.0kPa), and 5.1kPa (n = 5, SD = 2.1kPa), respectively. After week five, the vacuum levels in operatory One were found to be 1.7kPa and the filter element was replaced with a new one. The filter elements in operatories Two and Three were replaced after week seven when vacuum levels were found to be 4.4kPa and 3.4kPa respectively. After week number eight, operatories Four and Five had vacuum levels of 6.4kPa and 6.1kPa respectively, with the original filter element installed.

Table 2 – Calculated removal efficiencies $(B_{Hg} - F_{Hg})/B_{Hg} \times 100$; where B_{Hg} is the mean baseline Hg level and F_{Hg} is the mean amount of particulate Hg >(0.45 μm) collected after the chairside filter was installed

	50 μm filter	15 μm filter	1 μm filter	0.5 μm filter
Removal efficiency	92.7%	97.8%	98.4%	99.6%
ISO 11143 efficiency	–	94.8%	–	96.8%

ISO 11143 removal efficiencies for the 15 μm and 0.5 μm filter systems are also presented. The 50 μm and 1 μm filters were not tested with the ISO 11143 protocol.

3.3. *Part 3: ISO 11143 testing*

The 15μm and 0.5μm filters were evaluated using the ISO 11143 protocol. The 0.5μm filter passed the ISO protocol at 96.8% efficiency (97.5% with an empty separator and 96.8% with a full separator). The 15μm system had 96.1% efficiency with a full separator but only 94.8% when the separator was empty. The lower value of the two efficiencies calculated from the two test series (empty separator and full separator) is the reported efficiency of the separator. As a result, the 15μm filter did not pass the ISO 11143 protocol. Data from both clinical removal efficiency and ISO 11143 removal efficiency are presented in Table 2 for comparison.

4. Discussion

Increasingly, U.S. environmental regulators are requiring the installation of ISO 11143 tested amalgam separators in dental clinics to help diminish the release of Hg into WWTPs and septic systems. An array of products is available in the market, representing a range of both price and complexity (Fan et al.,

Table 3 – Vacuum levels in kilopascals (kPa) before (baseline) and after installation of 0.5 μm filters on five dental chairs

	Room One (kPa)	Room Two (kPa)	Room Three (kPa)	Room Four (kPa)	Room Five (kPa)	Mean (kPa)	SD (kPa)
Baseline	7.8	6.4	6.4	7.8	7.4	7.2	0.7
Time 0	7.1	6.4	6.1	6.8	6.8	6.6	0.4
1 Week	6.4	6.4	5.7	6.8	6.8	6.4	0.4
2 Week	6.4	5.1	5.7	6.8	6.4	6.1	0.7
3 Week	6.4	6.1	5.7	7.1	6.6	6.4	0.5
4 Week	4.7	5.4	5.4	7.1	6.6	5.8	1.0
5 Week	1.7	5.1	5.1	7.1	6.6	5.1	2.1
6 Week	–	4.7	5.1	6.8	6.6	–	–
7 Week	–	4.4	3.4	6.8	6.6	–	–
8 Week	–	–	–	6.4	6.1	–	–

Filter elements were replaced after week five in room one and after week seven in rooms two and three. The original filter elements were still in place after eight weeks in rooms four and five.

2002; Batchu et al., 2006a; Hylander et al., 2006). This study demonstrated that low-cost filtration systems can function as effective amalgam separators, removing substantial amounts of Hg-containing amalgam waste without degrading the chairside vacuum levels. Testing of the 0.5μm system demonstrated 99.6% removal efficiency in a clinical setting, and 96.8% efficiency when evaluated in the laboratory with the ISO 11143 protocol. An important caveat is that the calculated removal efficiencies do not include dissolved Hg species and particulate Hg less than 0.45μm. It is the Hg in these fractions that may be more reactive due to methylation and other chemical processes occurring in the aquatic environment.

Chairside amalgam separators have several advantages over central systems. Removing Hg-containing amalgam waste at the chair prevents the contamination of plumbing lines downstream of the dental-unit. The buildup of Hg-containing amalgam in wastewater lines can serve as a reservoir that leaches Hg, especially in the presence of oxidizing line cleaners (Kümmerer et al., 1997; Batchu et al., 2006b). There is evidence that amalgam in plumbing lines can leach Hg at levels that make uncleaned lines a hazardous waste under the Resource Conservation and Recovery Act (Stone, 2004). A second advantage of a chairside location is that maintenance of the separator is more convenient: there is no need to visit a utility room to check on the status of the separator. A third advantage is the low cost of consumables: replaceable filter elements are available from multiple commercial sources and cost is on the order of a few U.S. dollars per unit.

While filtration can remove substantial amounts of mercury-containing particulate from dental wastewater, dissolved species of Hg are also present (Stone et al., 2003; Stone, 2004), and their removal is not always easily achieved. In locations where strict discharge limits have been implemented, complex Hg separation systems that remove both particulate and soluble species may be indicated. There are several advanced mercury removal systems (AMRS) available commercially. These systems can be expensive to purchase and maintain as well as labor intensive to operate. Chairside amalgam separators, like the system described here, may be of benefit when used in combination with an AMRS. Chairside systems can prolong the lifespan of an AMRS by greatly reducing the amount of particulate to be removed.

Hg-contaminated consumables from all amalgam separation systems need to be appropriately managed. Used filter elements should be handled in accordance with federal, state, and local requirements. Since used filter elements can contain substantial amounts of mercury in the form of amalgam particulate, they should be handled in accordance with pertinent regulations. Used filter elements can be readily recycled to recover mercury and other metals found in amalgam.

The U.S. Navy is currently in the midst of a multiyear project to install amalgam separators in all Navy dental treatment facilities. The primary amalgam separator being installed is the chairside filtration system described above. In the few locations where the clinic is required to meet a specific Hg discharge limit, AMRS are installed in combination with the chairside filtration system. Currently, the Navy has installed 677 chairside systems, and feedback from the clinics has generally been favorable.

5. Conclusion

Low-cost chairside filtration systems are effective in removing substantial amounts of Hg from dental-unit wastewater. The filters retain amalgam waste at the chair, thereby limiting the deposition of amalgam in downstream plumbing lines where Hg could leach over time. The 0.5μm filtration system passed the ISO 11143 amalgam separator testing protocol. There was minimal impact on chairside vacuum quality at initial placement, with a gradual loss of vacuum performance over time.

Acknowledgements

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