

Mercury Contamination from Dental Amalgam

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Introduction

Mercury is a pervasive environmental pollutant that has a variety of adverse health effects in humans. Mercury has three forms: elemental, inorganic and organic, which each have their own profile of toxicity. Human exposure to mercury generally occurs by inhalation or ingestion.¹ According to the World Health Organization (WHO), the principal human exposure to mercury is from dental amalgams.² The WHO also lists mercury as one of their top ten chemicals of major health concern.³ Anthropogenic activities have nearly tripled the amount of atmospheric mercury and it is increasing at 1.5 percent annually. Once mercury enters the food chain it can bioaccumulate in humans and cause adverse health problems. Dental amalgam is a source of human exposure to elemental mercury.⁴

Dental amalgam has been used as a restorative treatment in dentistry for well over 170 years. It is a mixture of several metals, consisting of silver, tin, zinc, and copper; however, about 43-54% of the main component

Background. Mercury in dental amalgam is a hidden source of global mercury pollution, resulting from the illegal diversion of dental mercury into the artisanal and small-scale gold mining sector, to crematoria emissions from the deceased and sewage sludge that is sold to farmers. These significant mercury sources result in air, water, and food contamination that consequently have a negative impact on human health.

Objectives. The aim of the present study was to investigate and report on all of the various pathways mercury in dental amalgam can enter the environment.

Methods. The present study searched the electronic data bases of PubMed and Google Scholar. Peer reviewed journals and references of studies included for full-text review were examined for potentially relevant studies. Articles published between 2000 to 2018 were searched and specifically screened for articles that referenced “Dental Amalgam,” and the following key words in various combinations: “Minamata Convention on Mercury Treaty,” “Sewage Sludge,” “Cremation,” and “Artisanal and Small-Scale Gold Mining.” Data were included on the most populous countries of China, India, the United States, Brazil, and the European Union collectively. We also included data on cremation statistics and current global trends, looking at populations where cremation is a common practice, such as Japan and India.

Discussion. Dental amalgam represents a significant, but understudied area of global mercury pollution that includes cremation, sewage sludge, burial, and small-scale gold mining.

Conclusions. Mercury used in products and processes, including dental amalgams, is a global pollutant. Even after the last mercury dental amalgam is placed, its toxic legacy will continue for decades, because of its pervasive bioaccumulation in the environment. Government regulatory agencies should make it mandatory to utilize available technologies, not only in developing countries, but also in developed countries, to reduce mercury contamination.

Competing Interests. The authors declare no competing financial interests.

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is mercury.⁵ Dental amalgams are not inert, either chemically or environmentally. Dental amalgam enters discharge systems that contain sanitants, cleaners, and other compounds that can generate soluble and colloidal mercury, which will be mobilized into the environment. Environmental action includes erosion or oxidation (air and sunlight) and microbial transformations, which can also mobilize mercury into the environment. A review of

a study done by the Environmental Protection Agency (EPA) that estimated emissions from dental amalgam may have been significantly underestimated. The EPA’s previous study estimated that 0.6 tons/year of dental amalgam is being released, however, the present account indicates that between 6 and 35 tons of mercury is discharged into the environment from dental amalgam, which is considerably higher than the EPA’s estimate.⁶

The United Nations Environmental Programme (UNEP) reported that the dental sector uses about 340 tons of mercury in dental amalgams each year. It is estimated that 100 tons of dental mercury enters the waste stream annually.⁷ There are several serious problems that are created from dental amalgam pollution. First, mercury pollution is caused by the historical use of dental amalgam. Additionally, the current use adds up to mercury releases from historical practices. Some emissions associated with dental amalgam are from dental waste incineration, burial, cremation, and off-gassing of mercury from dental amalgam corrosion in the mouth.⁸

Cain *et al.* attempted to quantify mercury releases of the most significant categories of mercury-containing products, using a life cycle approach from production to disposal of these products in the US. They used substance flow models and estimated mercury releases for 1990, 2000, and 2005. Regarding the use and disposal of dental amalgam, human waste, tooth loss, cremation and infectious waste were considered. While these routes may result in significant releases of mercury, it was determined that cremation is the most critical. Additionally, their model calculated that approximately 150 kg of mercury is released annually in exhaled breath as a result of dental amalgam fillings.^{8,9}

Throughout the last several decades, mercury used in products and processes have had a tremendous impact on environmental mercury pollution. Dental amalgam amounts to about 1/5th of the global consumption of mercury. Mercury is a persistent toxic pollutant, traveling between the atmosphere, land, and water. The atmosphere is the principal transport route. Atmospheric mercury can globally transport for up to a year; therefore, mercury pollution created

Abbreviations

ASGM	Artisanal and small-scale gold mining	EPA	Environmental Protection Agency
DSRs	Dental surface restorations	UNEP	United Nations Environmental Programme

in one region can contaminate another through the air, at great distances from the original source.¹⁰

The aim of the present study was to investigate and report on the many different ways that mercury in dental amalgam enters the environment.

Methods

To our knowledge, this is the first paper to investigate and report on all of the various pathways mercury in dental amalgam enters the environment. The present study used the electronic data bases of PubMed and Google Scholar and searched for articles from peer reviewed journals. Additionally, references of studies included for full-text review were examined for potentially relevant studies. Articles published between 2000 to 2018 were searched and specifically screened for articles that referenced “Dental Amalgam,” and the following key words in various combinations: “Minamata Convention on Mercury Treaty,” “Sewage Sludge,” “Cremation,” and “Artisanal and Small-Scale Gold Mining.”

Due to a research gap, there were very few peer reviewed published articles in the areas of cremation, sewage sludge, and artisanal and small-scale gold mining (ASGM). Therefore, we also conducted a grey literature electronic search using targeted websites and Google search engines to access additional relevant sources. We used

the same key words and the different combinations as mentioned above. The full text of publications were screened that provided the following supplementary references from various governmental and non-governmental organizations including the Cremation Association of North America, the World Health Organization, the Food and Drug Administration, the United Nations Environmental Programme, the Arctic Monitoring and Assessment Programme, the European Commission, and the Environmental Protection Agency.

Data were included on the most populous countries of China, India, the United States (US), Brazil, and the European Union (EU) collectively, and their number of dental schools, as mercury use in dental amalgam is still being taught around the world. We also included data on cremation statistics and current global trends, looking at populations where cremation is a common practice, such as Japan and India. While some statistical data was found on cremation in terms of populations worldwide, information on mercury pollution from this source was woefully lacking and this lack of studies was consistently mentioned by the authors in the few articles that we found. Therefore, we included data on large-population studies on tooth surfaces restored with dental amalgam, because the legacy of dental amalgam will impact the environment over the life of the individual, and even after death.

There were no exclusions of the literature based on the country of origin, however, the majority of the included studies for this paper were from the US and the EU. Only English language articles were included. There exists a tremendous amount of research on mercury in general—we presented an overview on articles that were related to dental amalgam and how it enters the environment. Our search strategy is illustrated in Figure 1.

Results

A total of 433 articles were screened from PubMed and Google Scholar, as well as grey literature that included WHO, EPA, UNEP, Cremation Association of North America (CANA), government and non-government sources. After screening for duplicates, abstracts, and articles that did not meet the inclusion criteria, 59 articles were included (Table 1). The results of our research demonstrate that dental amalgam is an understudied source of mercury pollution in the environment. There is limited knowledge in its contribution to global air pollution through cremation, ground water and soil pollution from burial, sewage sludge that is sold to farmers, and the true amount being used in ASGM. Based on information from the various existing research that we found, cremation is a much larger source of global mercury pollution that continues to grow and needs further study. Our results lead to similar conclusions from the previous studies. The main limitation is the lack of research that is linked to the global pollution from this source in areas outside of the obvious, which is the dental office.

Discussion

The following sections discuss the various pathways that dental amalgam

has become a significant contributor of mercury pollution, and the lack of existing research.

Dental amalgam use globally

The current world population is more than 7.5 billion. In 2004, it was estimated that there were 1.8 million dentists around the globe.¹¹ China is the most populated country in the world; however, according to Huang *et al.*, in 2007 there were only 40 dental schools in the country.¹² The second most populated country, India, has over 1.3 billion people. India's dental industry has 289 dental schools, the most worldwide. According to Sandhu *et al.*, in the early 2000's there were approximately 26,000 graduating dentists annually.¹³ Toxics Link stated that in 2012, about 70% of the Indian population had cavities, and about 58% of that population went to a dentist for treatment. There were 121,000 listed dentists and the use of dental amalgam was estimated at 72 tons annually.¹⁴

In 2009, Saliba *et al.* reported that Brazil had more dental schools and graduated more dentists each year than the US and the EU combined, second only to India. Brazil's dental professionals represent 12% of all dental professionals in the world, having one of the largest numbers of dentists per capita globally.¹⁵ According to the American Student Dental Association, there are 66 dental schools in the US and Puerto Rico.¹⁶ The EU had more than 160 dental schools in 2009 as reported by Murtomaa.¹⁷ As of 2007, dental amalgam was the second largest use of mercury, after chlor-alkali production in the EU. This study estimated the range to be between 55 and 95 tons a year of mercury for dental use, with an average of 75 tons.⁸

The World Health Organization

confirmed that decreasing the use of dental amalgam is not only important in reducing human exposure, but also to lessen the considerable amount of mercury that is estimated to be released into the environment from this source. The use of dental amalgam and its applications, such as illegal sales and use in ASGM, improper waste management, or even through cremation, is contributing to the problem of global mercury pollution.¹⁸

Dental amalgams off-gas mercury vapor. The newer high copper amalgams are less stable and create a much greater release of mercury vapor. These amalgams emit about ten times more mercury than the mercury fillings prior to the 1970's.¹⁹ Estimates from the EU study suggest that dental amalgam is a major contributor to the overall EU environmental emissions of mercury from anthropogenic activities. Mercury released into the air can be partly deposited into other environmental locations such as soil, vegetation, or surface water.⁸

Dental amalgam and sewage sludge

The European Federation of National Associations of Water Services represents national drinking and waste water services for the public and private sector in 29 countries. In a 2016 document titled, "Dental Amalgam and Mercury Regulation", the European Federation of National Associations of Water Services advocated for a ban on dental amalgam in order to decrease mercury in the sludge from the wastewater treatment plants. They noted that the major source of the mercury in wastewater in most treatment plants in the EU is from dental amalgam.²⁰

According to the US EPA, dental offices contribute the largest source of mercury into sewage treatment plants. Nationally, dentists discharge

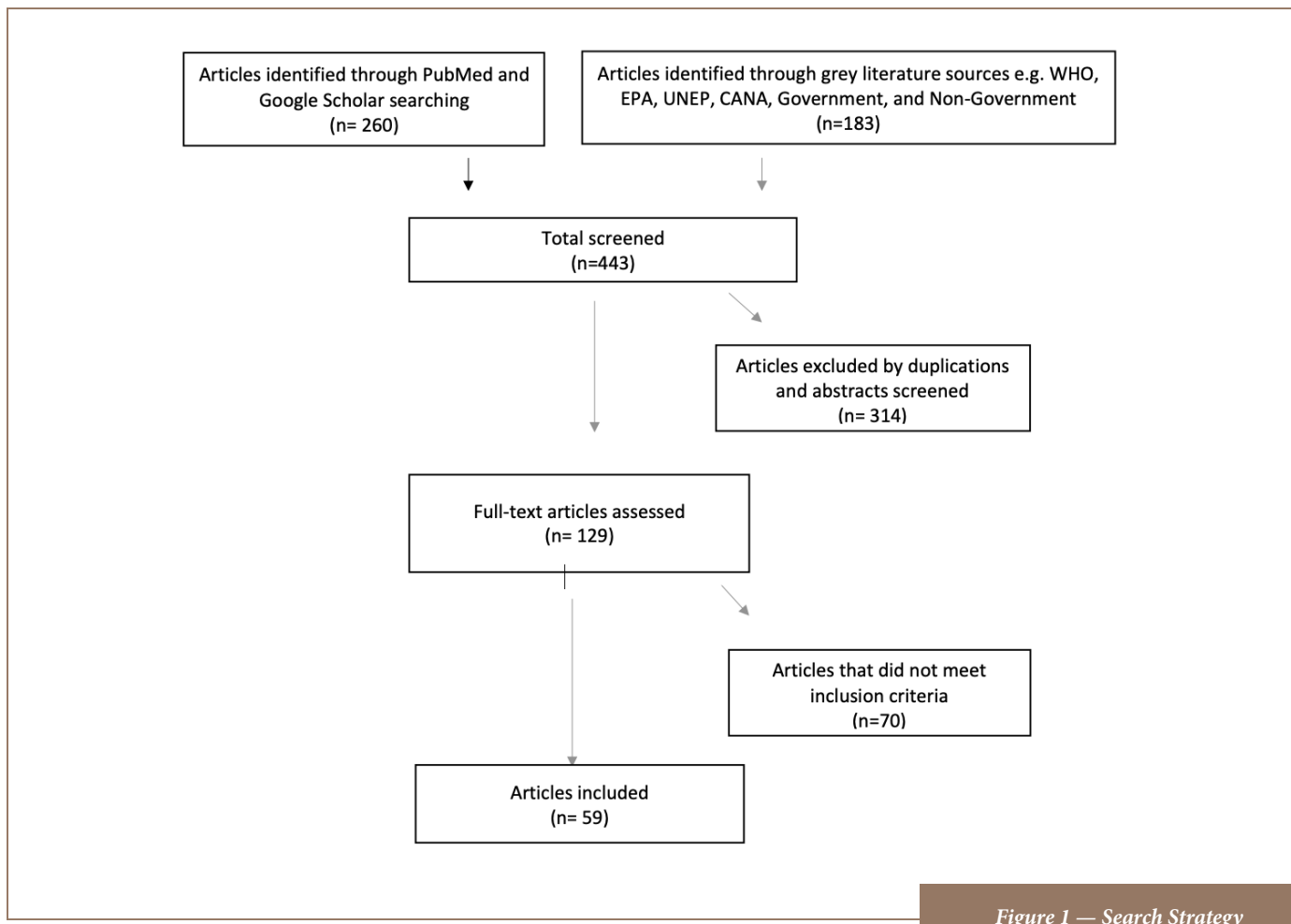


Figure 1 — Search Strategy

about 5.1 tons of mercury into publicly owned treatment works, and most of this mercury will end up in the environment.²¹ Once the amalgam waste has gone through the sewage treatment plant, the remaining amalgam waste becomes sewage sludge. This sewage sludge is then disposed of in landfills, incinerated, or sold as fertilizer for agriculture purposes. These pathways of disposal of sewage sludge release mercury into groundwater or air.²² Dentists typically dispose of excess amalgam into specific medical waste containers, however, if this waste is incorrectly disposed of, the amalgam may be incinerated, causing the mercury to enter the air where it will eventually end up in the water or

Study Source	Studies (n)	Countries (n)
PubMed/Google Scholar	25	15
Grey literature: World Health Organization (WHO), United States Environmental Protection Agency (USEPA), Cremation Association of North America, United Nations Environment Programme (UNEP), Government and non-Government	34	11
Total	59	21 (counting duplicate countries)

Table 1 — Included Studies

on land.²³

Dental amalgam and cremation

A substantial source of mercury pollution comes from cremation. Estimations of the amount of mercury released via this pathway vary considerably, due to the large number of dental restorations.²⁴ Cremation emissions add to both environmental pollution in areas close to the source and also countrywide emissions due to atmospheric transport. These emissions are deposited primarily through rain. Mercury is persistent and can change in the environment into methylmercury, which is extremely toxic.²⁵ During cremation, mercury will enter the process, since it is not only from dental amalgam in teeth, but also due to bioaccumulation of mercury in the body.¹⁴

Global cremation rates are increasing for various reasons, such as cost, consumer preferences for an easier, less formal funeral service, fewer religious restrictions, and environmental impact. India, where cremation is an ancient custom, and Japan, where it is the most common practice for disposing of human remains, have extremely high cremation rates. Meanwhile, Taiwan, Hong Kong and Switzerland have cremation rates of over 80%. Internationally, in concentrated urban areas, cremation rates are often greater than 70%. This is due to population density and lack of burial space. As of 2015, the national cremation rate in the US was expected to exceed burial rates and is projected to grow to 78% by 2035.²⁶

According to the European Environment Agency inventory guidebook in 2016, mercury in dental amalgams may contain 5 to 10 grams of mercury depending on the number of fillings and type of material used. The emissions factors from cremation

have a very high uncertainty due to the methods used, such as the operating temperature, residence time in the secondary combustion chamber, and fuel (such as fuel oils in Sweden or natural gas in North America). The extremely high variation is also due to limited testing performed to derive emission factors or design characteristics.²⁷

In 2005, the top three emission countries for all products and processes using mercury were China, India, and the US. At that time, cremation emissions were reported to be an average of 26 tons, ranging from 20 tons to 30 tons. This does not include additional releases from the production of mercury in dental amalgam, but indicates that this release amount is ambiguous.²⁸ A 2009 study projected that by 2012, 42% of the Indian population would have access to a dentist and estimated 574 tons of mercury in dental amalgam would be captured in the population, leading to a 2.8-fold increase of mercury in fillings since 2000. Using a conservative estimate of 50% mercury present in original fillings, it is estimated that India emits around 1.4 tons of mercury during cremations annually.¹⁴

A study in Switzerland estimated that each cremation released between 2 and 4 grams of mercury, with a maximum of 8.6 grams in an individual cremation.²⁴ In 2012, Richardson updated a risk assessment on mercury exposure and risk from dental mercury amalgam in the Canadian population that was originally published in 1996. New data became available from the Canadian Health Measures Survey (2007 to 2009) that specifically recorded the number of tooth surfaces restored with dental mercury amalgam. Based on the Canadian Health Measures Survey (CHMS) data, 17.7 million Canadians aged ≥ 6 years collectively carry 191.1 million mercury amalgam

surfaces, representing 76.4 million mercury amalgam-restored teeth. Like the EU report, Richardson stated that dental amalgam is a major source of mercury exposure in Canada.⁸ The values were lower than those reported in other studies, thereby reducing the potential for an overestimated calculation of mercury exposure to the Canadian population.²⁹ The Cremation Association of North America reported that in 2016 the percentage of cremation in Canada was 70.2% and was expected to increase to 79.8% by 2020.³⁰

Yin *et al.* used data collected by the National Health and Nutrition Examination Survey, which is similar to Canada's CHMS, to analyze associations of blood mercury, inorganic mercury, methylmercury, and bisphenol A with dental surface restorations (DSRs) in the US population. They looked at populations from 2003-2004, which showed that there were DSRs in 32%, 51%, 78% and 60% of those from 3-12, 13-21, 22-65, and over 66 years of age, respectively. In total, about 31% of subjects had 1-8 DSRs, and 28% had ≥ 8 DSRs. From 2011-2012, the percentages increased by approximately 10% as follows: 45%, 58%, 81%, and 64% DSRs for those from 3-12, 13-21, 22-65, and over 66 years of age, respectively. The increase in DSRs correlated with significantly elevated blood total mercury, inorganic mercury, and methyl mercury.³¹ As reported by the CANA, in 2016, the cremation rate in the US was 50.1%, and projected to be 56.3% by 2020.³⁰ This would also be indicative of an increase of atmospheric mercury pollution due an increase in cremations in the US and Canada over this period.

In 2015, the Ministry of Civil Affairs in China announced that of the 9.77 million Chinese who died in 2014, 4.46 million (45.6%) were cremated.³² Gworek *et al.* looked at various

pathways of air contamination by mercury and its transformations from both natural and anthropogenic sources, noting that it is difficult to distinguish between them. It was estimated that just one dentist using dental amalgam contributes about 3.4 g/day into the environment. Emissions from cremation go directly into the air, burial releases mercury into the soil and groundwater, and the dental office releases mercury into the soil, groundwater and air.³³ According to the Scientific Committee on Health and Environmental Risks, the demand for dental mercury amalgam in Japan has decreased from 5.2 tons in 1970 to 700 kg in 1999 and 314 in 2004. This reduction of dental amalgam will decrease atmospheric mercury pollution in the long-term future, since almost 100% of the Japanese population is cremated after death.³⁴

In 2010, data was compiled and reported by the Arctic Monitoring and Assessment Programme for the 2013 UNEP Global Mercury Assessment of various sources of anthropogenic mercury emissions by country, region, and industry sector. The top ten countries with mercury emissions from cremation were China (794.0 kg), India (607.7 kg), the US (437.8 kg), Mexico (113.6 kg), Vietnam (95.7 kg), the Philippines (94.3 kg), Canada (91.0 kg), the United Kingdom (85.8 kg), Australia (82.2 kg), and Russia (75.8 kg). The Arctic Monitoring and Assessment Programme's global total estimate of emissions for cremation was 3,582 kg.³⁵

A more recent look at dental amalgam was published in 2016 by the UNEP, titled "Lessons from countries phasing down dental amalgam use," which listed dental mercury amalgam emissions at between 50-70 metric tons a year into the atmosphere. They noted that the removal and replacement of old dental amalgam is not a closed

system, and that the waste and release of mercury generated in the dental sector is challenging to monitor and manage. The majority of mercury in dental amalgams (about 2/3rds) ultimately enters the environment.³⁶ This is also due to the increasing number of consumers seeking dental care, resulting in more teeth containing dental amalgam, which will continue to release mercury into the environment.⁹ The American Dental Association reports that many variables affect the longevity of dental mercury amalgam restorations, as they can last up to 40 years.³⁷

Health risks from mercury in cremation

Crematoriums have many risk factors, not just to the funeral workers, but also to the population in surrounding neighborhoods. Living near these environmental toxic exposures can have negative health effects, particularly in vulnerable subpopulations.³⁸ Corns *et al.* reported that while atmospheric mercury emissions in the United Kingdom (UK) fell from 40.7 tons to 6.9 tons between 1982 and 2001, mercury emissions from cremation have increased significantly. One estimate reported that annual emissions from 1982-2002 more than doubled from 0.36 tons to 0.82 tons, with little change in the number of cremations performed. They used the PS Analytical Sir Galahad amalgamation-atomic fluorescence spectrometer to study mercury emissions on a single crematory stack in the UK. It was determined that mercury was emitted in a short period of approximately 40 minutes into the cremation process. The concentrations emitted varied significantly, but could be as high as several mg/m³. Both elemental and ionic mercury were emitted during the cremation process. The ratio of the two forms depended on the total level of mercury being

emitted.³⁹

Mari *et al.* reported that as of 2010, there were over 1000 crematoriums in Europe, while in 2006, China had 1549 and Japan had 1500. Toxic emissions from cremation include persistent organic pollutants such as combustion gases, polychlorinated dibenzo-p-dioxins and dibenzofurans, and heavy metals. These toxins stand out because of their ability to bioaccumulate in humans; however, mercury is the most significant of these pollutants.⁴⁰ In 2010, the CANA estimated that there were 2204 crematoriums in the US, an increase from 1971 in 2005.⁴¹

Exposure to mercury has been associated with over 250 symptoms in humans, resulting in complications for proper diagnoses. Mercury can be quickly removed from the blood and transported and sequestered into various tissues; in other words, there may not be a direct correlation between blood mercury concentration and the gravity of mercury poisoning.³ There are serious health risks associated with populations who are exposed to mercury emissions from crematoriums. Low-level exposure to vaporized metallic mercury can be inhaled, causing mercury poisoning. The principal toxic effects of this exposure include excitability, tremors, and gingivitis. Exposure to vaporized metallic mercury can also be toxic to the immune system, nervous system, kidneys, cardiovascular system, gastrointestinal system, lungs, muscle, liver, blood cell count, skin, and eyes. Human fetuses and small children who are exposed are more likely to have mercury concentrated in the brain and kidney.⁴²

Heavy exposure to mercury vapor (approximately 5-10 mg/m³ or higher) inhaled directly from heating metallic mercury may cause erosive bronchitis, and bronchiolitis will occur

in a few hours, followed by interstitial pneumonitis and, ultimately, respiratory distress. If a large enough quantity of mercury is inhaled, renal failure can develop.⁴³

Kato *et al.* conducted a study to assess workers' exposure to nanoparticles released in crematoriums. They measured nanoparticle exposure in crematoriums and estimated the respiratory deposition of nanoparticles by number and size distribution. Field surveys revealed the inhalation exposure during each working process. They found that alveolar exposure during the cremation process was significantly higher than that in other respiratory regions.⁴⁴ Crematorium workers, especially administrators, have significantly higher mercury levels in their hair, particularly those who worked in a closed environment with limited air ventilation.⁴⁵ Vaporization or the burning of mercury-containing materials can form toxic vapors. These vapors can enter the respiratory system and pass effortlessly into the circulatory system. Studies have shown that even chronic inhalation of low concentrations of mercury can produce tremors, sleep disturbances, and impaired cognitive skills in workers.^{4,42} Inhalation of mercury vapor can cause necrotizing bronchitis and pneumonitis, which can result in respiratory failure. Mercury is neurotoxic, and can be highly devastating, especially in the central and peripheral nervous systems of children.^{43,46}

A retrospective cohort study by Dummer *et al.* investigated the risk of stillbirth, neonatal death, and lethal congenital anomaly among babies of mothers who lived close to incinerators and crematoriums in Cumbria, northwest England, from 1956-1993. They found that during that time frame there was a substantial increased risk of stillbirth for those

closer to crematoriums, consistently increasing from 1961 forward. The risk of anencephalus also increased significantly from 1961-1971. From 1972 on, there was an increased risk of all other congenital anomalies, excluding neural tube and heart defects, with increasing proximity to crematoriums, which was considerable for the period of 1983-1993.⁴⁷

In 2012, the Crematorium Working Group reported that crematoria are significant sources of mercury, dioxin, and particulate matter. Incineration of bodies, body parts, and infectious and chemotherapeutic wastes collectively represent the second largest known source of dioxin and mercury pollution in the US. The World Health Organization, the US EPA and other public health experts consider any level, no matter how low, of emissions of mercury, dioxins, furans, and particulate matter from incineration to be a threat to human health. Vulnerable populations such as babies, children, women of childbearing age, and the elderly are particularly at risk from exposure to these toxins. Employees who work in these environments, as well as those populations who live near the source are exposed to higher levels of these pollutants.^{40,42,48} The effects of mercury vapor exposure can last long after the exposure has ended. While typical symptoms and signs, such as tremors, gingivitis and salivation may quickly disappear after exposure has stopped, mechanisms of long-lasting or remote effects have not been investigated. This is possibly due to the damage caused by mercury vapor exposure remaining for a long period of time, or by mercury remaining in the body and continuing to cause adverse effects, or to the prior exposure somehow stimulating aging, resulting in poorer neurobehavioral performance.^{42,43}

The final report of the Senate

Crematoria Study Committee was prepared in 2012. This report noted that while there are emissions of other chemicals during the cremation process, mercury is of the most concern to communities near crematoriums. When mercury is burned, it becomes a colorless and odorless gas that can travel long distances. While mercury exposure has the potential to cause a variety of health problems, the brain and kidneys are especially vulnerable. According to Dr. Anne Summers of the University of Georgia, there is no known lower level for toxicity of mercury, and scientists clearly agree that mercury toxicity can have serious consequences on human health.^{4,42,49}

Dental amalgam diverted to artisanal small-scale gold mining

Artisanal small-scale gold mining is the largest source of mercury emissions worldwide. Artisanal small-scale gold mining is active in approximately 70 countries throughout Asia, Latin America, and Africa. Around 15 million people are estimated to be working in this sector and about 5 million are women and children. Artisanal small-scale gold mining has devastating effects not only to the local inhabitants, but also to the environment, especially rivers, due to mining locations. It is estimated that 400 metric tons of gold is produced worldwide through ASGM.⁵⁰ In 2006, the UNEP reported on the global impact of mercury supply and demand in ASGM. The official amount of mercury imported in Brazil (2005) was 43.3 tons of mercury, with the majority of the mercury coming from Spain and the UK. While this mercury was identified for dental usage, most ends up in ASGM, even though it is illegal to mine with mercury in Brazil.⁵¹

Research shows that populations in these areas, as well as those downstream, eat fish that are highly

mercury toxic. These communities are also subjected to tremendously harmful levels of mercury vapor, causing neurological, kidney, and possibly immunotoxic/autoimmune effects from mercury exposure.⁵² According to Esdaile *et al.*, the approximate amount of mercury released through ASGM is between 410-1400 tons annually, which is about 37% of total global mercury emissions. Easy access to mercury, along with its low cost and the soaring price of gold make this a sustainable livelihood for miners. For the above reasons, the Minamata Convention has made reforming this sector a priority.⁵³

Steckling *et al.* looked at chronic mercury intoxication in Zimbabwe, one of the top 10 countries that use mercury for gold extraction. It was estimated that Zimbabwe used 25 tons of mercury annually in ASGM. The study found that miners had 72% chronic mercury intoxication, while the controls showed none. They stated that in 2004, chronic mercury intoxication was likely one of the top 20 leading causes of disability for the population in Zimbabwe.⁵⁴

Mercury-free alternatives in artisanal small-scale gold mining

A 2018 report by the UNEP titled “Going for gold: can small-scale mines be mercury free?” investigated the plight of ASGM workers and their unregulated worksites. As demonstrated in this report, mercury pollution due to ASGM activities is an enormous worldwide problem, and cyanide pollution is a concern as well. It is estimated that the global workforce in ASGM indirectly supports over 100 million people in rural economies. Under the Minamata Convention, these methods of gold mining are considered “worst practices”. Thirty-two countries have begun working on national action plans to counter mercury pollution. The UN and the Global Environment Facility are financing projects to teach

best practices and helping to facilitate mercury-free mining.⁵⁵

The EPA published a report offering mercury-free techniques for miners, suggesting that using alternatives to mercury may allow for higher gold prices. Some recommendations are the use of concentration methods, increasing the amount of gold in ore or sediment by selectively removing lighter particles. Panning uses water to separate heavy gold particles from lighter ones. Sluicing uses water to wash ore down a series of platforms, where gold will sink and be captured, normally by a carpet. Shaking tables, spiral concentrators, vortex concentrators, centrifuges, magnets, and flotation are other methods that have been developed that do not use mercury.⁵⁶

An alternative to mercury in ASGM is the borax method. Gold is gravitationally separated by sluicing and panning, with iron shavings possibly removed by a magnet, then gold concentrates are mixed with an equal mass of borax. This mixture is heated and the gold solidifies in a relatively pure form when cooled. The borax complexes to silicate and oxide impurities. The authors recommend that this chemistry problem be addressed in the Chemistry and related fields to devise solutions that are “low-cost, easy to use, and provide immediate and obvious benefits to the miners.”⁵³

A study by Drace *et al.* investigated four ASGM sites in Mozambique. Clean Tech Mining used new technology that eliminated the use of mercury in all of their mining practices. This was done by utilizing magnets to manually separate the magnetic gangue materials from the gold. The owner, a former miner, used his own resources to fund this project and has developed a viable and sustainable mining operation that

is not only safe for employees, but also safe for the environment.⁵⁷

Mercury-free dental materials

Mercury free dental materials have been widely used and available for many decades. Atraumatic restorative treatment, a non-mercury dental filling technique, was developed in the 1980's in Tanzania as a minimally invasive way to fill teeth. Using atraumatic restorative treatment saves teeth that would have otherwise been extracted due to decay. It is a viable solution for dental treatment, particularly in developing countries or in countries with emerging economies. Atraumatic restorative treatment requires no electricity, water, or conventional dental equipment. Only hand instruments are needed to clean the decay and a high-viscosity glass-ionomer is then placed in the tooth. Atraumatic restorative treatment is a proven restorative dental technique that has been successfully used in developing countries around the world, and is also being used in developed countries.⁵⁸ There are other mercury-free dental restorative materials, such as resin composites made from plastic resin and powdered glass. These materials are strong and are tooth-colored. Another common material is glass ionomer cement, which is a mixture of acid and powdered glass, that is durable and also tooth-colored. Additionally, dental materials such as zinc oxide-eugenol cements, polyacid-modified resin composite, also known as compomer, and resin modified glass-ionomer cement are commonly used worldwide.^{18,59}

Conclusions

Mercury use in products and processes, including dental amalgams, is a cradle-to-grave deadly poison and a global pollutant. Even after the last mercury dental amalgam is placed, its toxic legacy will continue

for decades, because of its pervasive bioaccumulation in the environment. Due to the ratification of the Minamata Convention, many mercury-containing products and processes will be banned in 2020, including medical devices such as thermometers and manometers, as well as mercury in soaps and cosmetics. However, dental amalgam is only listed as a phase down product. On July 1, 2018, the EU banned the use of dental amalgam for children under 15 years of age, and pregnant and breast-feeding women. Other countries are banning bulk mercury for dental use, which will make it more difficult to use in ASGM. Affordable mercury-free dental restorative materials are widely available, even for developing countries and countries with emerging economies. By ending the use of dental amalgam, the current illegal flow from that source into ASGM will be eliminated, which will help promote existing non-mercury mining methods. As reported, the practice of cremation is growing around the world. Estimations of the total amount of mercury released during cremation vary greatly due to a lack of monitoring, as well as uncertainty over the total body burden of mercury in the deceased. Technology, however, is available to mitigate the discharge of mercury into the atmosphere from crematoriums. Mercury amalgam separators for dental offices are recommended in accordance with the Minamata Convention, as part of the mercury reduction into the environment from this source. While mercury amalgam separators will decrease mercury from dental offices, dental amalgam can still enter wastewater from human waste and sewage sludge, which will either end up in the land via fertilizer, or landfills or air through incineration. At the Conference of the Parties second meeting of the Minamata Treaty, a recommendation was brought to the plenary that harmonized customs codes for dental amalgam to include

not only bulk mercury for dental use, but also encapsulated dental amalgam. This would assist in the tracking of mercury for dental use around the globe. Government regulatory agencies should make the use of available technologies mandatory, not only in developing countries, but also in developed countries to reduce mercury contamination. All countries can stop the use of dental amalgam, as proven by Norway, Denmark, and Sweden. This can be achieved by using mercury-free alternatives such as atraumatic restorative treatment, thereby eliminating a major source of mercury pollution.

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