Reducing Lead Exposure from Drinking Water: Recent History and Current Status

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SYNOPSIS

This article discusses the issue of lead contamination of drinking water, noting the various regulatory-driven measures that have been adopted in the U.S. since 1986 to address this public health issue. The article summarizes the literature on the dynamics of tap water lead contamination and discusses this widespread source of lead exposure in the context of the latest research evidence.

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The concern about lead contamination of drinking water in North America as a significant public health problem has generally followed the improved medical understanding of the neurological damage caused by even low levels of lead exposure. The first major initiative in the U.S. to control lead in drinking water was the "Federal Lead Ban," a set of Amendments to the Safe Drinking Water Act, signed into law in December 1986 with a state-level enforcement deadline of July 1, 1988.[1] These amendments banned the use of solders and flux containing more than 0.2% lead (solders and flux were typically composed of 40% to 50% lead) and restricted the allowable amount of lead to less than 8% in any brass or other material intended to be in contact with water. Before the Federal Lead Ban went into effect, lead in drinking water had been regulated under the 1975 National Interim Primary Drinking Water Regulations. These earlier regulations were inadequate because they mandated lead monitoring at a distribution system's entrance point rather than at the consumer's tap. This monitoring did not take into account the lead that entered drinking water through corrosion of materials in the distribution system.[2]

Shortly after the Federal Lead Ban was passed, a flurry of medical and epidemiological studies began to appear showing that lead was causing measurable neurological damage, especially in infants and young children, at far lower exposure levels than previously documented. Bellinger et al. in 1987 and McMichael et al. in 1988 observed clear IQ, cognitive development index, and learning deficits in young children at blood lead levels (BLLs) as low as 6 μg/dl, BLLs readily achievable just from the consumption of lead-contaminated drinking water.[3,4] In 1990, Needleman et al. demonstrated that children with elevated BLLs at age 9 had higher dropout rates, greater frequency of delinquent or aggressive behavior, and higher rates of learning deficits at age 19 than control groups.[5] By 1991, with publication by Needleman and Bellinger of a comprehensive review of the health effects of low-level lead exposure,[6] it had been established that the lead levels commonly found in U.S. drinking water were sufficient to contribute significantly to the widespread public health problem of elevated BLLs in children.[7]

In 1988, another important lead regulation was promulgated to protect the health of children. The Lead Contamination Control Act (LCCA) was designed to assist schools in implementing measures to test for and reduce lead contamination in drinking water from water coolers and other sources.[8] The Act required the Environmental Protection Agency (EPA) to publish a guidance document and testing protocol to assist schools in determining the source and extent of lead contamination in their drinking water. The Act required the EPA to identify and publish a list of brands and models of water coolers that contained lead, including those with lead-lined tanks. The LCCA also imposed civil and criminal penalties on the manufacture and sale of lead-containing water coolers. It also directed the Consumer Product Safety Commission (CPSC) to issue an order requiring water cooler manufacturers and importers to repair, replace, or provide refunds for water coolers containing lead-lined tanks.

MORE RECENT ACTIONS TO REDUCE LEAD EXPOSURE FROM DRINKING WATER

By 1990, with the increased awareness of the contribution of drinking water to the overall childhood lead exposure problem, there was considerable pressure from medical, public health, and parent organizations for the EPA and the public water supply industry to take further actions to reduce lead in drinking water. From a regulatory perspective, this was viewed as a formidable challenge by the EPA given that finished water (i.e., water leaving a water treatment plant) seldom contains detectable lead. Instead, lead contamination nearly always results from contact with building plumbing systems, which are beyond the regulatory authority of the EPA and the states. Action was clearly needed, however, and in June 1991, the EPA issued the federal Lead and Copper Rule, which mandated some creative and nontraditional approaches to achieving a projected 50% reduction in U.S. drinking water lead exposure by the end of the decade.[9] The Rule requires each public water supply system to assess the severity of lead contamination in the higher-risk residences on its system. If more than 10% of the residences have first-draw lead levels (i.e., following a standing time in the plumbing system of at least six hours) exceeding a concentration of 15 μg/l (the non-health-based "action level," projected by the EPA to be exceeded by about 25% of systems), the public water supplier is required to: (*1*) provide warning notices to all customers with encouragement to test their individual home's water for lead; (*2*) determine experimentally (using "pipeloop tests"), or based on studies conducted by similar water utilities, what treatment modifications could be implemented (e.g., pH or alkalinity adjustment or introduction of film-forming phosphate or silicate-based corrosion inhibitors) to reduce lead corrosivity and thus potentially at-the-tap lead levels; and (*3*) implement these corrosion-optimization methods and monitor at-the-tap lead levels to determine the effectiveness of the treatment modifications.

The EPA also developed helpful scientifically based guidance to assist water suppliers in this lead reduction effort using established water chemistry principles.[10] The Lead and Copper Rule estimated that 14% to 20% of the total U.S. lead exposure was from drinking water.[9] All very large water suppliers are required to try to reduce the lead corrosivity of their finished water, even if their water does not exceed the official action level.[9] In the event that the water exceeds the lead action level after optimal corrosion control treatments are employed, a water supply system is required to replace lead service lines in its distribution system.

Much research has been done on factors that contribute to corrosion as well as possible treatments to reduce the lead-leaching corrosivity in water systems. Studies have found that the amount of lead leached from brass fixtures depends on pH; alkalinity; concentrations of sulfate, chloride, and orthophosphate; and the presence of natural organic matter.[11] To combat the corrosivity problem, water distribution systems began adding chemicals such as phosphoric acid, ortho-phosphoric acid, zinc orthophosphate, polyphosphate, and silicates, or mixtures of these chemicals. It soon became apparent that successfully reducing residential tap water lead levels through treatment optimization was a "hit-or-miss" proposition. While some cities, such as Seattle and Norfolk, Virginia, were able to dramatically reduce average residential lead levels,[12] an extensive EPA-funded study of more than 1,000 public water supply systems conducted by our research group at the University of North Carolina (UNC)–Asheville Environmental Quality Institute (EQI) found that residential tap water lead levels were only slightly more likely to decrease following corrosion control than to remain constant or even increase.[13] Of particular concern was the statistical finding that the use of zinc orthophosphate (the most popular corrosion inhibitor employed at the time) was almost equally likely to be associated with either a decrease or an increase in average residential lead levels. The challenge is that phosphate- and silicate-based "film-forming" corrosion inhibitors can range (with very small or subtle changes in water chemistry) from one extreme of forming a thick film on the inside of pipes and residential plumbing systems close to the treatment plant, to the other extreme of staying indefinitely in a dissolved state and thus never filming out at all. Using a database of more than 10,000 U.S. residences, our research team also found that, although about 10.2% of homes had first-draw lead levels >15 μg/l, in 83% of cases the level could be reduced to <15 μg/l simply by running the tap for one full minute.[13] Not surprisingly, testing by the District of Columbia Water and Sewer Authority similarly showed an even greater reduction in lead levels with longer water flushing; in an analysis of 96 residences, a 95% reduction in lead was achieved when water was flushed for 10 minutes.[14] These findings strongly suggest that childhood tap water lead exposure, especially in homes without lead service lines, can usually be reduced greatly simply by providing families with a two-sample test that shows them whether they have a tap water lead contamination problem and, if so, whether the exposure can be reduced sufficiently simply by flushing the water for a specified length of time prior to use, e.g., one minute. In fact, the federal Lead and Copper Rule specifies that public water supplies that exceed the action level must advise customers to have a first-draw and one-minute-flush lead test conducted on their tap water.[9] Many households have followed this recommendation, including tens of thousands that have used the residential testing opportunity offered by our research laboratory.

Extensive research has shown that the build-up of lead in drinking water from residential plumbing systems is kinetically very nonlinear, with typically more than 60% of an eight-hour overnight dwell concentration present after a one-hour internal dwell (i.e., standing time or stagnation period), and 25% to 30% present after just a 10-minute internal dwell time.[15] These results indicate that to avoid tap water lead exposure in a time- and water-efficient manner, residents in homes with high first-draw and low one-minute flushed-line lead concentrations should fill a container with one-minute flushed-line water and use this for subsequent drinking and cooking rather than having to re-flush the system prior to each water use.

During the late 1980s and early 1990s, drinking water quality researchers began to notice that lead solder joints and older lead pipe were not the only significant sources of tap water lead contamination in North American households. Virtually all brass plumbing parts were (and the majority still are) composed of alloys containing 5% to 7% lead (as allowed under the Federal Lead Ban), and even with this relatively low lead content, they discharge substantial concentrations of lead into drinking water, especially if the home is served by more corrosive water. Lead contributions from leaded brass faucet fixtures were first studied from 1989 to 1993.[16–18] These findings led to the filing of a lawsuit against faucet manufacturers in California under that state's Proposition 65 referendum, which specifies that a product may discharge no more than 0.5 μg/day of lead into drinking water.[19] This litigation was settled in June 1995, with faucet manufacturers agreeing to a very low lead discharge standard (achievable only with no-lead-added or very-low-lead brass alloys).[20] Later research by the EQI using sampling data from more than 570 California residences showed that, on average, about 16% of the lead in the first liter of water drawn after at least a six-hour dwell time originated from the faucet fixture.[21] Although the 1995 settlement required only that lead be removed from brass faucets sold in California, the cost associated with separate manufacturing, distribution, and recycling facilities, combined with growing public awareness of the issue, resulted in a decision by virtually all North American and European faucet companies to reformulate entirely to no-lead (typically containing about 0.1% to 0.2% lead as an incidental impurity) or to low-lead (typically 1.0% to 2.5% lead) alloys for the entire North American market between 1996 and 1999. Thus, tap water lead exposure from this source has been reduced significantly for homes with faucets installed subsequent to these reductions.

Another brass product that has come under Proposition 65 scrutiny in California is leaded-brass water meters. Research has shown that these meters, traditionally manufactured using alloys containing 5% to 7% brass, also discharge substantial amounts of lead into household water.[22,23] Discharge concentrations were found to decrease for about four months with the installation of a new meter,[22] and then to remain essentially constant for the entire service life of the meter (typically 20 to 40 years).[23] The long-term concentrations of lead discharged ranged from <5 μg/l to 40–50 μg/l depending on the corrosivity of the public water supply. As a result of the settlement of a Proposition 65 lawsuit in 1999, only no-lead brass water meters can now legally be sold in California, and one company (Neptune) now sells only no-lead meters worldwide.

CURRENT STATUS AND ACTIVITIES

While the actions to ban lead solder, reduce the corrosivity of public water supplies, and remove lead from brass faucets and water meters over the past two decades have significantly reduced tap water lead exposure in the U.S., further reductions are needed to better protect the health of children. Studies are now finding that even very low-level lead exposures cause neurological, learning, and IQ deficits in children. Lanphear et al. in 2000 reported measurable learning (especially reading) deficits at BLLs <5 μg/dl.[24] Given that it has been estimated that a child's BLL is increased by approximately 0.16 μg/dl for each μg/day ingested,[25] a long-term lead ingestion of only 31.2 μg/day (e.g., from two liters of water, each with a lead concentration of approximately 15.6 μg/l) is required to produce a BLL of 5.0 μg/dl. Even more important in terms of the significance of tap water lead exposure is the 2003 work of Canfield et al., who found a 7.4-point reduction in measured IQ with a BLL increase from 1 μg/dl to 10 μg/dl.[26] This work is of special significance because it strongly indicates that the relationship between BLLs and IQ deficits is not linear; rather, the first small elevation of BLL in young children apparently causes most of the neurological damage, with additional higher exposures causing disproportionately less additional IQ reduction. This finding suggests the possibility of a more important role for the relatively smaller exposures resulting from drinking water, as compared to exposure due to lead-based paint, since at least some measurable exposure from drinking water reaches the majority of North American children.

If the 2003 Canfield et al. nonlinearity findings are correct, then the 14% to 20% of total lead exposure attributable to drinking water[9] may well be responsible for a disproportionately high proportion of the childhood neurological, IQ, and learning deficits caused by lead in the U.S. Thus, it is important to address even some of the relatively smaller sources of lead in drinking water. Recent work by our research team shows that the lead discharged into households from leaded-brass cut-off, gate, ball, and angle-stop valves, which are dispersed throughout the typical residential plumbing system, is sufficient to measurably elevate BLLs in household occupants.[27] Using the study results from Canfield et al.,[26] we have also observed that the combination of a leaded-brass water meter and leaded-brass water service parts (e.g., brass curbstops, elbows, t-sections, meter and curbstop tailpieces, corporation stops) discharges enough lead into the typical household to produce a 0.5-point to 2.5-point IQ deficit in young children consuming a total of two liters of water per day from water and food.[28] (Water-absorbing food sources include noodles, rice, frozen orange juice, etc.) Fortunately, no-lead water service parts are now readily available from at least three North American manufacturers, and a rapidly increasing number of cities, including Los Angeles, Detroit, Bangor, Honolulu, and Quebec City, have either switched or are in the process of switching to no-lead water service parts and water meters. Proposition 65 litigations are also underway in California to require the sale of only no-lead household valves and water service parts in that state.

The presence of lead in drinking water is still a very significant health issue despite the actions that have been taken over the years to control the problem. Evidence of this can be seen in the recent concern over lead service lines in Washington, D.C. In late 2003, water samples tested by the District of Columbia Water and Sewer Authority (DCWASA) showed lead levels above the 15 parts per billion (ppb) EPA action level in many homes and buildings in the city. Since the discovery, DCWASA has been replacing lead service lines, has provided water filters to homes with lead service lines, and has added phosphoric acid to the water to reduce corrosivity. An expert panel convened by DCWASA concluded that the chloramines the city began using in 2001 to disinfect its water increased the corrosivity of the water, therefore allowing high levels of lead to leach out of lead service lines.[29] This is a very significant situation because at least 400 other public water suppliers have switched to chloramine disinfection since 2000, and thus the problem may prove to be widespread. There is a pressing need for additional research on this issue.

CASE STUDY: NEW YORK CITY

The various actions described above have contributed to a reduction in tap water lead exposure in the U.S. Indeed, even if no actions had been taken except to discontinue the use of lead-based plumbing solder, lead levels would gradually decrease even in older homes, since eventually available lead would dissolve out of the plumbing system. Unfortunately, however, there exists no statistically reliable long-term database on residential lead levels from which decreases can be quantified. From 1992 to about 1996, lead levels in "high risk" (i.e., plumbed with lead solder between 1982 and 1986) residences were tracked under the Federal Lead and Copper Rule requirement by most public water systems. However, since then most systems have fallen back to greatly reduced monitoring, and the responsibility for keeping long-term continuous records has fallen to often already understaffed state water supply departments. We surveyed six states and found that none could produce meaningful records of public water supply lead levels for the period 1991–2003. After the very difficult to access Federal Lead and Copper Rule records, the next largest national database of residential tap water lead levels is our own at EQI, which includes data on more than 120,000 residences sampled from 1988 to the present. Unfortunately, the great majority of these residential tests were conducted in the period from 1990 to 1994 when there was the most public and media attention on the issue. Since that time, requests for residential testing have gradually dwindled, and the post-1995 data are largely clustered around specific dates and specific cities where public attention and concern were piqued by media coverage of the issue.

The city of New York, however, is a notable exception to the lack of monitoring. Since early 1995, the city has been very progressive and proactive on this issue by offering free tap water testing to all residents, and the analytical work and data-keeping have been largely coordinated at the EQI. New York City provides an excellent case study opportunity, both because of the thousands of residences tested over time and because the entire city is served with finished water of relatively stable chemical composition derived from just a few raw water sources.

Since New York City began offering free testing to all residents in early 1995, about 20,000 residents have taken advantage of the opportunity. Even before that time, a sufficient number (for analysis of statistical trends) of city residents took advantage of EQI's national research program, which offers low-cost residential testing. From 1992 to the present, for each residence, first-draw and one-minute flush lead concentrations have been measured and the data stored along with information on the age, location, and size of the building; the composition of plumbing system materials; and other water quality variables such as pH and concentration of orthophosphate.

New York City had begun to take some first measures to reduce water corrosivity in late 1991 with the addition of sodium hydroxide. This was done primarily to offset the pH-reducing effects of fluoride addition and probably had no effects on lead levels. As shown in the Figure, residential tap water lead data were first available in 1992, when a median first-draw concentration of 4.0 μg/l was observed. Beginning in late 1992 and continuing through mid-1993, New York City began adding ortho-phosphoric acid on an experimental and irregular basis. However, in 1993 the city began to add this corrosion inhibitor continuously to essentially the entire water distribution system. As seen from the Figure, median first-draw lead concentrations decreased by 42% from 1992 to 1994. Although median concentrations increased slightly in 1995, from 1996 through 2003 median levels were constant at about 1.5 μg/l, a 62% decrease from 1992.

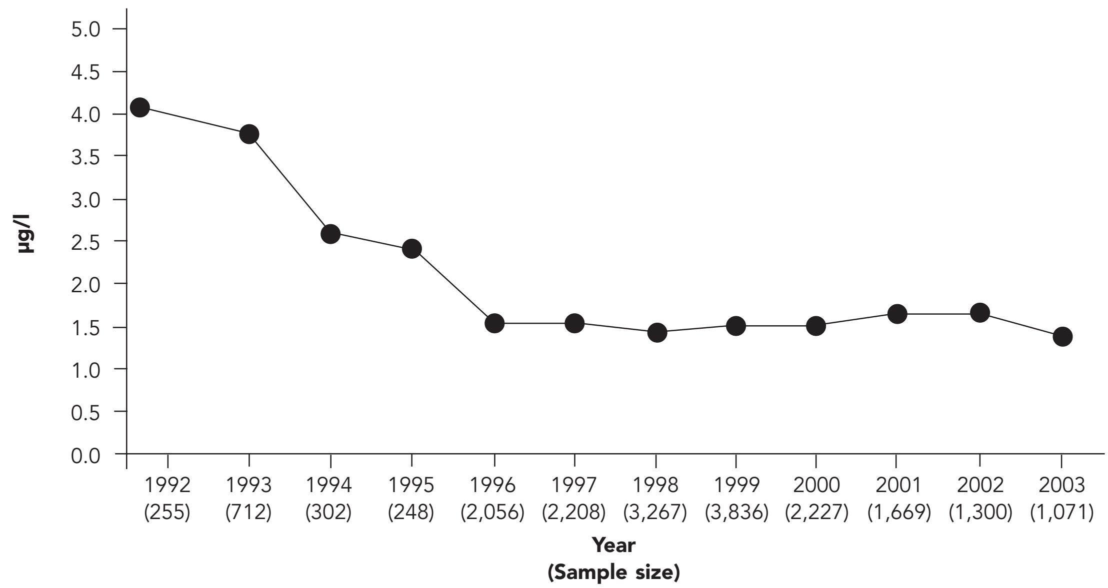
The constant tap water lead levels from 1996 through 2003 suggest that the combined effect of (*1*) the gradual replacement of older leaded-brass faucet fixtures by newer no-lead fixtures, (*2*) the slight aging of plumbing systems, and (*3*) the addition of new non-lead-solder buildings, were not enough to cause further lead reductions during this period. New York City had much less growth during this period than Sunbelt or Western U.S. cities, where extensive new housing stocks would be expected to have caused greater decreases in median lead tap water levels from 1996 to 2003. The Figure suggests that New York City's ortho-phosphoric acid corrosion reduction program has been relatively and consistently effective. It should be noted, however, that our data show that as of 2003, approximately 15% of residences still had first-draw tap water lead levels >10 μg/l.

SUMMARY AND CONCLUSIONS

Nationally, lead exposure from drinking water has been recognized as a substantial (14% to 20% of total[9]) contributor to overall childhood lead exposure in the U.S. Although no reliable national statistical trend data have been published to date, average tap water levels in the U.S. as a whole have almost certainly decreased since the mid-1980s, as in New York City, through the banning of lead solder, the introduction of corrosion-reduction measures by public water systems, and the discontinuation of leaded-brass faucet fixtures. However, during the same period, medical and epidemiological studies have determined that even very low-level lead exposures cause substantial and permanent IQ and learning deficits in young children, and that low-level but widespread lead exposures, such as from drinking water, may have disproportionately large health effects. Thus, lead in drinking water should still be considered an important public health issue to be addressed. Our experience since 1988 indicates that the most powerful and cost-effective measure for further reducing exposure from drinking water may be to encourage and enable households to test their water for lead. A two-sample test determines whether a household has a tap water lead problem and whether exposure can by avoided by flushing the tap for a specified length of time, e.g., one minute. Our experience is that, with this information alone, children's residential exposure to lead via tap water can be virtually eliminated.

New York City has been proactive in offering tap water lead testing to residents, with more than 20,000 residents taking advantage of this opportunity to date. Other cities would be wise to follow New York's lead. Primarily through corrosion control measures, New York City has also been able to reduce median tap water lead levels by more than 60% since 1992, which is probably typical for U.S. public water suppliers that have optimized their water treatment for lead corrosion. It should be remembered, however, that the estimated 50 million North American households with individual or private water supplies have seen less of a reduction in tap water lead, if any.

Figure. Median lead concentration in first-draw residential water samples, New York City, 1992–2003



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