Health Impacts of Lead in Drinking Water

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Introduction
While Canadian blood lead levels have declined significantly over the last three decades, exposure to lead continues to be a concern (Health Canada, 2013a). The adverse health effects from exposure to lead are well-documented in children and adults (Brown and Marolis, 2012; Health Canada, 2013a; WHO, 2010). Lead adversely affects those that are most vulnerable in our society: infants, children and pregnant women, racialized individuals, newcomers, and individuals experiencing low income and poor nutrition (Health Canada, 201a; WHO, 2010). Health effects have been associated with blood lead levels as low as 1-2 µg/dL (Health Canada, 2013a); levels which are currently present in Canadians. Accordingly, additional measures to further reduce remaining lead exposure to Canadians are warranted (Health Canada, 2013a).

Although the average lead concentration in Toronto's drinking water is considered to be low, drinking water is considered to be an important source of exposure to lead when lead service lines or other lead-bearing materials are present in the plumbing system. Public health efforts are directed at eliminating and reducing remaining exposure before they occur, including the need to reduce lead concentrations in drinking water as much as possible (Barn and Kosatsky, 2011; Brown and Marolis, 2012).

Blood Lead Levels Over Time
Blood lead levels among the Canadian general population have decreased substantially from a mean of 4.8µg/dL in 1979 to a mean of 1.3µg/dL\textsuperscript{1}. The percentage of the population with blood lead levels greater than 10 µg/dL\textsuperscript{2} decreased from 27% to less than 1% during this time period (Bushnik et al., 2010). This decline in Canada as well as many countries around the world is largely attributed to the phase out of leaded gasoline in the 1970's and a ban on leaded solder used in canned foods, and restrictions on lead in paint.

The Health Effects Associated with Exposure to Lead
Lead is one of the most extensively studied toxic chemicals. Comprehensive reviews on lead have been recently conducted by the National Toxicity Program (NTP, 2012), Health Canada (Health Canada, 2013a), and the US EPA (US EPA, 2013).

The adverse health effects from exposure to lead are well-documented in children and adults (Brown and Marolis, 2012; WHO, 2010). Lead is associated with multiple health effects on multiple organ systems at both elevated and at typical levels of exposure (Health Canada, 2013a). At extremely elevated levels, lead can lead to seizures and ultimately death. At low levels of lead exposure, there is a large body of evidence to demonstrate that lead is associated with a number of different neurological and developmental outcomes (Bellinger, 2011; Health Canada, 2013a; NTP, 2012; US EPA, 2013). The strongest evidence for health effects in children at low levels of exposure include: reduced intelligence, attention deficit hyperactivity disorder (ADHD), conduct disorder, and aggression and delinquency (Health Canada, 2013a; NTP, 2012). For adults the effects include: increased all-cause mortality and dysfunction in the

\textsuperscript{1} Blood lead levels taken in 2007-2009 - cycle 1 of the Canada Health Measures Survey (CHMS), participants ages - 7 to 69 years. The 95\textsuperscript{th} confidence intervals for the mean blood lead level were 1.2-1.4. The 95\textsuperscript{th} percentile blood lead level for cycle 1 was 3.7 µg/dL (95% CI: 3.3 – 4.2). In cycle 2 of the CMHC (2009 – 2011, participants ages – 3 to 69 years) the geomean of all participants was 1.2 µg/dL (95% CI:1.1 – 1.2) with a 3.2 µg/dL 95th percentile (95% CI: 2.9 – 3.4) (Health Canada, 2013b).

\textsuperscript{2} The blood lead intervention level in Canada is 10 µg/dL, established in 1994. This value is currently under revision. The US CDC uses a blood lead "reference value" of 5 µg/dL to identify children and pregnant and lactating women with blood lead levels that are much higher than most individual's levels (CDC, 2010; CDC, 2012).
renal, cardiovascular, reproductive, central nervous systems (Bellinger, 2011), with the strongest evidence at low levels of exposure for decreased renal function (NTP, 2012).

**Vulnerable Populations**
Fetuses and children are particularly vulnerable to the effects of lead because they are at an increased risk of exposure and also have greater susceptibility to the toxic effects. Research shows that those that are already experiencing other vulnerabilities (i.e., individuals experiencing low income, poor nutrition, newcomers, racialized individuals) are the most at risk from exposure to lead (CDC, 2005; Health Canada, 2013a; Pfadenhauer et al., 2014; WHO, 2010).

Children tend to have more hand to mouth behaviour, consume more dust and dirt, spend more time in one environment and are more likely to have nutritional deficiencies increasing their absorption of lead. In addition, children have enhanced absorption of lead through their gastrointestinal tract in comparison to adults (WHO, 2010). Children also have a smaller body weight relative to their intake of lead when compared to adults.

It has been shown the lead passes into the placenta, with levels being measured in the fetal brain as early as the first trimester. Prenatal effects of lead exposure on neurodevelopment have been demonstrated in epidemiological studies (CDC, 2010). This exposure is concerning since fetuses and children are going through critical stages of development with important windows of vulnerability (WHO, 2010). The NTP (2012) found the strong evidence of effects at low levels of exposure to lead for reduced fetal growth.

Socioeconomic status is a significant risk factor for both lead exposure, absorption and a greater susceptibility to the harmful effects of lead (WHO, 2010). In addition, multiple studies have shown that neurodevelopment deficits in children from lower socioeconomic strata are greater in magnitude than those from higher strata at a given blood lead level (Health Canada, 2013a; NTP, 2012). The possible reasons behind this finding include co-exposure to other neurotoxicants, fewer opportunities for stimulation, reduced nutritional status, and increased stress or reduced coping resources (Bellinger, 2008).

Studies in the United States have found a high prevalence of elevated blood lead levels in newcomer populations. The majority of these observations have been in refugee children (CDC, 2005; Esenberg et al., 2011) but high blood lead levels have also been found in internationally adopted children (Aaronson et al., 2000), immigrant pregnant women (Klitzman et al., 2002) and children with a foreign birthplace (Tehranifar et al., 2008). The Canadian Health Measures Survey found that people who were born outside of Canada had higher mean blood lead levels than those who were born in Canada (Bushnik et al., 2010).

Nutrition can also impact lead levels with a diet low in calcium, iron and zinc associated with elevated blood lead levels (Health Canada, 2013a; NTP, 2012). Lead is primarily stored in bones, with the circulating blood representing only 1% of the total body burden of lead (Health Canada, 2013a). The half life of lead in blood is 30 days and in bone is approximately 10 to 30 years (NTP, 2012). Lead release from bone into the blood stream occurs at higher rate during times of poor nutrition, pregnancy and lactation, menopause, andropause and post-menopause (Health Canada, 2013a). Health Canada notes that those vulnerable populations that are susceptible to kidney dysfunction (those with hypertension, diabetes, and/or chronic kidney disease are more
susceptible to the toxic effects of lead, even at low levels of exposure in adults (blood lead levels of < 5 μg/dL) (Health Canada, 2013a).

**Drinking Water as a Source of Lead Exposure**

Today, the main routes of lead exposure for the general adult population are from ingestion of food and drinking water. For infants and children, the primary routes of exposure are food, drinking water, and the incidental ingestion of house dust, lead-based paint, soil, and consumer products (Health Canada, 2013a).

Public health agencies around the world identify drinking water as a significant source of exposure to lead when there are lead constituents in the plumbing system (Health Canada, 2013a; NTP, 2012; WHO, 2011). Lead may be introduced into drinking water as a result of dissolution from lead water service lines (pipe that runs from the water main to the household water meter), lead-based solders used to join pipes within homes and buildings, and plumbing fittings, faucets, and components containing lead. A recent study in an old Montreal neighbourhood demonstrated that drinking water flowing through lead service lines was a significant source of exposure to lead and a significant contributor to children's blood lead levels (Levallois et al., 2014). The amount of lead leaching from these sources is affected by a number of factors, including the age of the plumbing system, the chemistry of the water (e.g., pH, buffering capacity/alkalinity, suspended solids), water temperature, and the length of time the water sits in the pipes. The levels of lead in drinking water are lower in new houses as the two dominant sources of lead in the system, lead water service lines and lead solder, were phased out of use in Ontario in the mid-1950s and 1989, respectively.

Recently, researchers have recognized the potential for drinking water to be the dominant source of lead for formula-fed infants (Brown and Margolis, 2012; Triantafyllidou and Edwards, 2012). Triantafyllidou and Edwards (2012) estimated that drinking water can contribute 90 percent of a formula-fed infant's total exposure to lead (assuming powered formula reconstituted with drinking water). A recent study of schools in British Columbia estimated that drinking water contributed more than 50%³ of total exposure to lead for an elementary school aged child (6 to 11 years old) (Barn et al., 2014). The authors note that their study illustrates how exposure to lead concentrations in water, when greatly elevated, can substantially increase a child's overall daily lead intake (Barn et al., 2014).

**Associations between Lead in Drinking Water and Health Effects**

There are a number of studies that explore the association between blood lead levels and levels of lead in drinking water. Triantafyllidou and Edwards (2012) provide a recent critical review of the literature, concluding that lead in drinking water is positively and significantly associated with blood lead levels. This review also concludes that when drinking water levels of lead are elevated, drinking water can be the dominant, or a major contributor to elevated blood lead. Health Canada (2013a) provides a summary of Canadian studies of lead in drinking water and the impact on blood lead levels. However, it is noted that the impact of low levels of lead in drinking water on blood lead levels has been rarely studied (Levallois et al., 2014).

A recent Canadian study examined the relative importance of low levels of lead in drinking water to children’s blood lead levels (Levallois et al., 2014). Three hundred and six children,

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³ Based on the pre-flushed lead in drinking water values.
aged 1 to 5 years, living in old boroughs of Montreal and currently drinking tap water from house with lead service lines were enrolled in a cross-sectional study. The age of housing included in the study (1920 to 1949) allowed the researchers to explore the relative importance of two primary sources of indoor lead contamination: lead paint and lead pipes. Drinking water, house dust, paint and children’s blood lead were concurrently collected from each child and respective household enrolled in the study.

The study found low levels of lead in the drinking water (mean: 0.89 ppb and 1.91 ppb, flushed for 5 minutes and 30 minutes of stagnation, respectively). Levallois et al., (2014) found an association between elevated blood lead levels (defined as ≥ 75th percentile (1.78 μg/dL)) and drinking water levels of lead when the water concentration was > 3.3 ppb: adjusted OR = 4.7 (95% CI: 2.1-10.2)\(^4\). Windowsill dust loading (> 14.1 μg/ft\(^2\)) was also associated with elevated blood lead levels: adjusted OR = 3.2 (95% CI: 1.3-7.8). The authors concluded that despite relative low levels, tap water contributed to an increase in blood lead levels in exposed young children.

A blood lead study conducted in Hamilton, Ontario from 2008 to 2009 found that drinking water, household dust, and yard soil were all significant predictors of children's blood lead levels (n = 643) (Richardson et al. 2011). However, when all three sources were considered concurrently and while controlling for modifying factors in a multivariate analysis, drinking water and household dust were the only sources of exposure that remained significant predictors of children's blood lead levels (Richardson, 2011). The drinking water concentrations in this study were generally below the drinking water quality standard of 10ppb. The geometric mean for BLLs in the study area was 2.23 ppb with less than 1% of children (n=6) with elevated blood lead levels\(^5\) (as defined by ≥ 10 μg/dL).

Other studies focus on the impact of exposure to very high levels of lead. For example, Edwards (2014) conducted a recent study exploring the association between high lead in drinking water levels experienced in Washington DC and adverse reproductive outcomes. Edwards (2014) explored fetal death and reduced birth rates between 2000-2003 during the period when Washington DC was experiencing very high lead levels in drinking water due to a change in disinfection practice and before the city was instituting risk mitigation\(^6\); and between 2007 and 2009, when partial lead service line replacements were being conducted in the absence of risk mitigation. Water samples often contained over 100 ppb and as much as 190,000 ppb lead (Triantafyllidou and Edwards, 2011). The 90th percentile water concentration was 40 ppb from 2001 to 2004, with a peak of 79 ppb in 2001 (Edwards, 2014).

Edwards (2014) found that the fetal death rate increased 32-63% (12.9 per thousand births) from pre 1999 levels to 2001 (the year with the highest lead in drinking water levels (9.7, 9.5, 7.9 per thousand births for 1997, 1998 and 1999, respectively). Lead levels in drinking water dropped in 2004 to levels below 1999 rates once public health interventions were instituted. Fetal death rates rose again (21-42% to 9.9 – 10.1 per thousand births in 2007 to 2008) when risks of high lead

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\(^4\) Multivariate logistic regression was used to evaluate the association between elevated blood lead levels in the children (defined as ≥ 75th percentile) and indoor lead contamination by means of odds ratio (OR) using the 95% confidence intervals (CI).

\(^5\) Capillary samples.

\(^6\) Unprecedented interventions by Washington DC Department of Health: written and broadcast warnings to avoid tap water, provision of free filters to each household, flushing of pipes
levels in water were again elevated in Washington DC due to partial lead service line replacements (in the absence of risk management). The limitations to this study due to the ecologic study design mean that a causal relationship between lead exposure and adverse pregnancy outcomes cannot be concluded, however, the authors suggest further work in this area is warranted.

The U.S. Centres for Disease Control and Prevention also studied the impact of the elevated drinking water levels in Washington DC between 1998 and 2006 on the blood lead levels of children. The study found that children tested after a partial replacement of their lead service lines were more than 3 times as likely to have an elevated blood lead level (as defined by ≥ 10 µg/dL) compared with children who lived in a house without a lead service line (odds ratio [OR] 3.3, CI 2.2-4.9) (Brown et al. 2011). A similar result was observed in North Carolina, where the impact of chloramines on children's blood lead levels was mitigated in newer housing, where the presence of lead service lines and lead solder was unlikely (Miranda et al. 2007). Edwards also explored the effect of the public health interventions on children's blood lead levels. The interventions were associated with a reduced incidence of childhood lead poisoning (Edwards et al., 2007).

**Limitations to the Evidence**

There are a few limitations to the evidence that should be considered when interpreting the findings. The mechanisms that influence the release of lead into the drinking water system are highly complex and site-specific. Studies to examine the issue are challenging due to the intensity of the sampling protocol (Brown and Margolis, 2012; Triantafyllidou and Edwards, 2012). Moreover, researchers have identified significant issues in the methods used to collect, store and analyze lead in drinking water (US EPA SAB, 2011). Methods used to sample blood lead levels are equally fraught with uncertainties (Health Canada, 2013a).

**Effectiveness of Mitigation Strategies to Reduce Lead in Drinking Water**

**Exposures to Lead and Drinking Water and the Impact of Lead Service Replacements**

In 2011, the US Environmental Protection Agency (US EPA) convened a Science Advisory Board (SAB) to review the evidence on partial lead service line replacement and report back to advise the US EPA Office of Water. The US EPA SAB concluded that partial lead service line replacement often causes drinking water levels of lead to significantly increase for a period of days to weeks, or even for a longer duration. The risks of immediate spikes in lead from the physical disturbance of the pipe during lead service line replacements are well known (US EPA SAB, 2011; Health Canada, 2009). The US EPA SAB note that the health risks associated with even relatively short-term exposure to lead could be substantial depending on the magnitude and duration of elevated lead levels, the water intake and vulnerability of the person exposed. It has been broadly assumed that this practice results in health benefits through a reduction in the amount of lead in the system (US EPA, 2000). These spikes in lead concentrations were assumed to be acceptable as acute exposure to lead was considered not as relevant as chronic exposure; however, this assumption is being reconsidered in light of a new understanding of the toxicity of lead (US EPA SAB, 2011).

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7 Immediate is defined as within the first few days after disturbance of the pipe.
Research has emerged to suggest that partial lead service line replacement may also pose a risk of longer-term releases of lead into the drinking water (Triantafyllidou and Edwards, 2012; US EPA, 2011; OMOE, undated). The potential for longer-term risks was raised by the US Centre for Disease Control (CDC) in June 2010 (US CDC, 2010). Since that time, there has been significant debate and dialogue among regulators, experts and drinking water suppliers on the merits of the partial lead service line replacement programs and the policies designed to encourage them.

The longer-term releases of lead into the drinking water are thought to occur due to contact between the new copper and the old lead parts of the services line (US EPA SAB, 2011; OMOE, undated). The available data suggest that elevated drinking water levels of lead tend to gradually stabilize over time, sometimes to levels below and sometimes at levels similar to those before the partial replacement (US EPA SAB, 2011). The ultimate goal is the removal of all lead pipes and components from water supply systems (Hayes and Hoskstra, 2010) as it offers a permanent solution to elevated lead in drinking water, but is associated with high costs (Barn and Kosatsky, 2011).

Reducing Exposures to Lead in Drinking Water through Corrosion Control

Corrosion control is a strategy that can reduce the release of lead from the various sources of lead in drinking water. Hayes and Hoskstra (2010) note that dosing of orthophosphate, the most effective corrosion inhibitor, can achieve over 99% compliance with the drinking water standard, with risk reductions in the range of 100 to 500 fold. Numerous studies have found associations between lowered blood lead levels and a reduction of lead in drinking water concentrations in response to corrosion control (Triantafyllidou and Edwards, 2012). Barn et al. (2014) also note that corrosion control is likely to result in a more effective and consistent solution to addressing elevated lead levels in schools when compared to flushing.

Lead as a Public Health Concern

Despite important actions to remove lead sources from the general environment (e.g., lead solder and lead in gasoline) and restrict the lead content of consumer product (e.g., lead in paint and consumer products), lead exposure continues to be an important issue (Levallois et al., 2014).

The reduction in population blood lead concentrations and the resulting evolution of our understanding of the toxicology of lead has resulted in a paradigm shift from managing symptomatic lead “poisoning” in exposed individuals to primary prevention of asymptomatic population health effects (American Association of Pediatrics, 2005). Lead toxicity was historically understood in dichotomous terms that were consistent with the medical model of disease at the time (i.e., a person was either poisoned or they were not). Recent science has challenged this thinking and supports a more nuanced understanding of lead toxicity as a continuum of adverse effects whose severity is contingent on the magnitude, timing, and duration of exposure. Given the health effects from prenatal and childhood exposure to lead and the effects that can occur even at low levels, many health authorities argue that reducing this preventable source of exposure should be a public health priority (Barns et al., 2014).

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8 For example, partial lead service line replacements are sometimes mandatory in the United States (US Lead and Copper Rule, US EPA, 2000). In Ontario, they are considered in cases where corrosion control cannot achieve the necessary reduction in lead concentrations (Ontario Safe Drinking Water Act, 2002).
Health Canada (2013c) estimates an overall economic benefit of over $9 billion dollars per year if exposure to lead is eliminated. This economic benefit is based on estimates of lead exposure and decrements to IQ in children and the present value of foregone lifetime earnings resulting from reduced intellectual development. Experts estimate that the cost of reducing lead in drinking is approximately $3 US/per person/year with a cost benefit of approximately $12 US/per person/year (Levin, R pers comm. 2009).

Public health efforts are directed at eliminating and reducing exposure before it occurs, including the need to reduce lead concentrations in drinking water as much as possible (Barn and Kosatsky, 2011; Brown and Marolis, 2012). It is recognized that the most cost effective and health protective approach to reducing environmental lead exposure is primary prevention (American Association of Pediatrics, 2005; ACCLPP, 2012). Health effects are associated with blood lead levels as low as 1-2 µg/dL; blood lead levels which are currently measured in Canadians. Accordingly, additional measures to further reduce remaining lead exposure to Canadians are warranted (Health Canada, 2013a).
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