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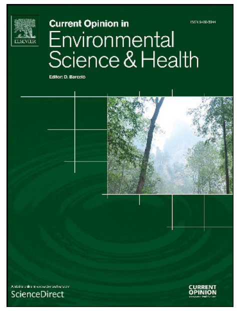

Lead in drinking water – an ongoing public health concern?

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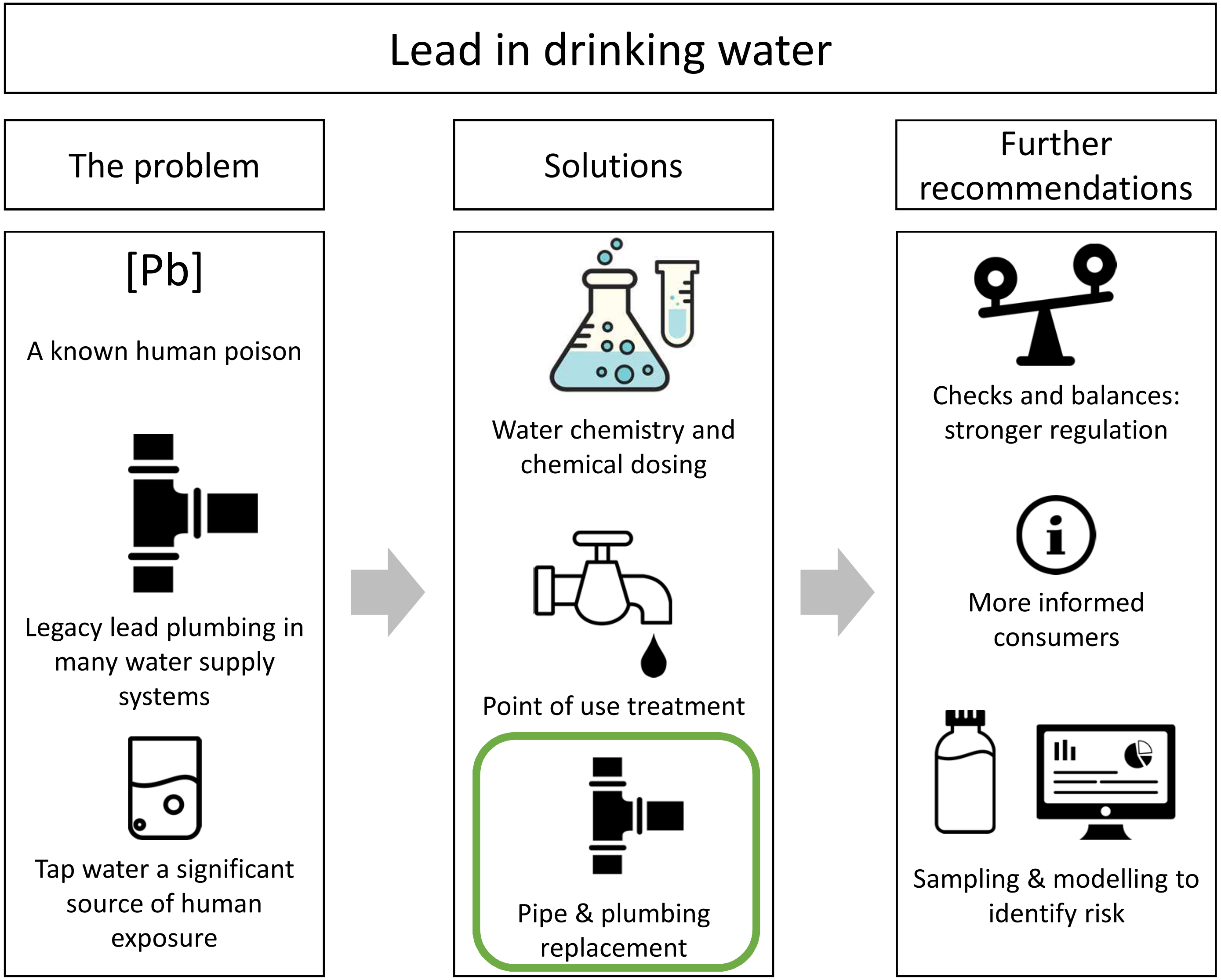
Lead in drinking water
The problem
Solutions
Further recommendations
[Pb]
A known human poison
Legacy lead plumbing in many water supply systems
Tap water a significant source of human exposure
Water chemistry and chemical dosing
Point of use treatment
Pipe & plumbing replacement
Checks and balances: stronger regulation
More informed consumers
Sampling & modelling to identify risk

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Lead in drinking water – an ongoing public health concern?

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Abstract

Lead remains a problem in drinking water in many parts of the world, with millions of properties served by distribution systems containing leaded components. This review considers the latest information on lead in drinking water and presents perspectives on solving the lead problem. Strong links have been established between human exposure to lead and health impacts, both in adults and children. As a result, permissible levels of lead in drinking water have generally become lower. However, achieving these regulations is challenging with the controls available. Future recommendations for aspiring to zero lead in drinking water are i) improved sampling, monitoring and modelling; ii) wider application of point of use devices in the short term; iii) replacement of all lead pipes and plumbing through enforceable regulation and heightened public awareness.

Keywords: Lead, drinking water, potable water, sampling

1. Introduction

Lead in drinking water is predominantly a human made problem. We have known that lead can cause adverse health effects for more than 2000 years but continued to use lead widely in water distribution and plumbing systems until only a few decades ago [1,2**]. However, this has left a huge 'legacy' problem, with components of water distribution still containing lead in many parts of the world (Figure 1). For example, it has been estimated that there may be between 6.1-10.2 million lead service pipes in the USA [3] and up to 9 million homes in the UK may be affected by lead pipes [4*]. Across Europe, estimates of between 0 and 50% of properties may be served by water supply from lead communication pipes [5]. This proportion differs from country to country, with some countries such as Denmark having largely removed all known lead pipes. However, this occurrence data is generally of quite poor quality and in many cases reliant on old information of unknown provenance. While the documentation is poor it can be anticipated that lead plumbing and fittings will be found in many places where there are old buildings. Incidents due to inappropriate use of lead solder and high lead copper alloy pipes and fittings have also given rise to problems in many parts of the world [6].

While a broad understanding on the extent of leaded pipes and plumbing is available in Europe, North America and Australasia, there is even less information available in Africa, Asia and South America. However, lead exposure is a known concern in many of these places. For example, nearly all African countries have deemed lead exposure to be a public health concern reported [7]. Exposure arises from a variety of sources, including from leaded paints, the disposal of hazardous wastes and contaminated water sources.

While lead is not typically found in raw water sources or water leaving drinking water treatment works (WTWs) [8**], localised contamination of water sources can be a significant problem, particularly in low- and middle-income countries [9]. This aspect is not the main focus of this review, but it is important to acknowledge and recognise that more effort is needed to improve such deteriorated water sources. For example, elevated levels of lead have been found in the water in the city of Addis Ababa at an average of 62.6 µg/L, this included sources supplying schools [10]. Multiple examples of lead contamination of water sources used for drinking in Africa have been recorded [6, 9].

The World Health Organisation (WHO) recognise lead as one of ten chemicals of major concern for public health [11] and has been highlighted as one of the most dangerous environmental poisons [12]. This review considers the latest evidence of lead in drinking water from pipes and plumbing, considering future perspectives on how the lead problem can be resolved.

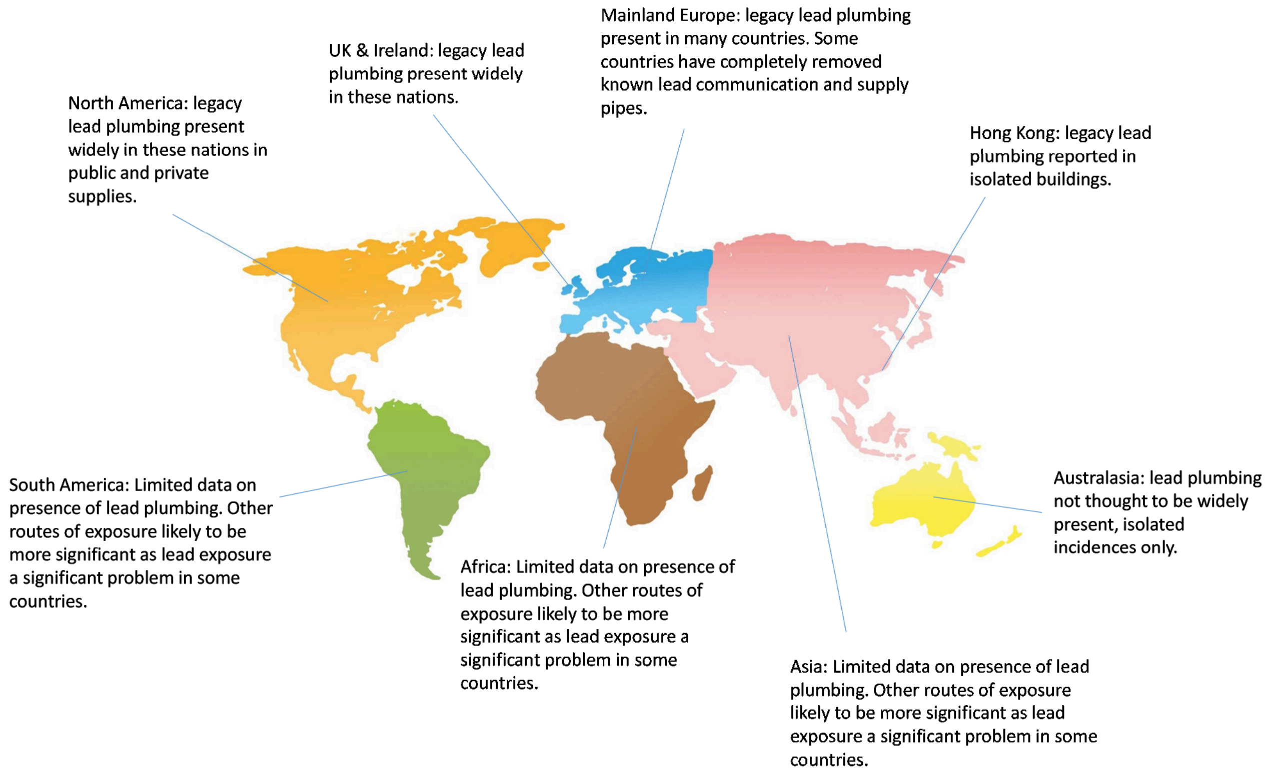

Figure 1. Presence of lead plumbing in water supply systems across the world.

2. Impact of lead on human health

Lead has the capacity to cause significant adverse impacts on learning and reduced intelligence quotient (IQ) in children and increased systolic blood pressure in adults, while other health impacts have also been associated with blood lead concentrations as low as 1-2 µg/dL [13]. The WHO/United Nations Expert Committee on Food Additives and Contaminants (JECFA) estimated that the previously established provisional tolerable weekly intake of 25 µg Pb/kg body weight is associated with a decrease of at least 3 (IQ) points in children and an increase in systolic blood pressure of approximately 3 mmHg in adults [14]. They note that while these may be considered small, taken in the broad population context they are significant. A recent study suggested that up to 400,000 people in the USA die from causes attributable to low level lead exposure each year, or at least in which lead exposure was a contributory factor, principally from cardiovascular diseases [15]. Many health bodies now advocate that there is no known safe limit of lead exposure, with a reference blood lead level of 5 µg/dL in children to identify those with elevated lead intakes [11,16].

3. Lead in drinking water

Regulatory standards for lead in drinking water have become more stringent as our understanding of the harmful impacts of lead exposure on health and development have emerged. The most recent guideline value for lead in drinking water from the WHO is 10 µg/L but is no longer a health-based value and has been designated provisional [17]. It was retained based on practical achievability in systems that still had lead pipes. However, it is on the basis of the requirement to achieve as low a level as reasonably practical. As a consequence, the European Commission adopted a standard of 10 µg/L Pb in drinking water on the same basis, but with an aspirational value of 5 µg/L that will come into force 15 years after the introduction of the revised directive [18]. In the US, the lead copper rule stipulates that action to control corrosion must be undertaken if Pb concentrations exceed an action level of 15 µg/L in more than 10% of customers taps sampled in a supply system [19, 20*]. The US Environmental Protection Agency (EPA) have also set an aspirational maximum contaminant level target of 0 (zero) lead in drinking water [21].

Overall, human exposure to lead has reduced as the result of successful public health campaigns to reduce lead in paint and petrol, with the result that the proportional contribution of exposure from tap water may have increased in many places [2**, 8**]. The detection of lead in drinking water remains a problem in locations where lead plumbing is still widely prevalent. The main cause of lead entering into drinking water is from the dissolution of lead from oxidation layers in plumbing materials (including lead pipework, solders and various fixtures and fittings) and from the release of particulate scale fragments from these components [22, 23, 24]. Recent high-profile incidences of elevated lead levels in drinking water in North America (Washington D.C 2000-2004 and Flint 2014-2016) and Asia (Hong Kong, 2015) highlight that this contaminant remains of significant concern, particularly in countries that still have a high proportion of lead communication and supply pipes [8**, 25*, 26, 27]. Many countries also have a reliance on private well water for many of their population. In the US, it has been estimated that 13% of households rely on unregulated wells for water supply. In these cases, there is a 25% increased risk that children from these households will have elevated blood lead levels [28] due to lead components in local distribution, including household plumbing.

Significant efforts have been made to reduce lead entering drinking water by changing water chemistry, primarily through raising water pH and through the addition of orthophosphate before water enters the distribution system [29, 30]. These efforts have been widely successful in reducing lead concentrations to be compliant with regulations [4*]. However, as has been shown in many studies, changes in disinfection regime and/or water quality characteristics can rapidly destabilise lead scale equilibria, causing significant increases in water lead concentrations [8**, 31]. Chemical dosing using orthophosphate and raising water pH is currently the best available approach to control plumbosolvency and should always be implemented where there is a known lead problem. However, it should be acknowledged that chemical dosing will only take us so far, particularly as regulations move towards 5 μg/L and lower. As we move towards these improved standards, it is unlikely that chemical interventions will guarantee compliance if lead and lead-containing components remain part of our water supply systems. This is evidenced from some surveys that report a significant minority of samples above 5 μg/L from properties where water has been dosed with orthophosphate [4*].

4. Future perspective: how do we get to zero lead in drinking water?

4.1 Sampling and monitoring

Currently, lead samples are taken from a single location very infrequently and are sent away for analysis leading to a significant lag before information on lead concentrations are available. In addition, a one-off lead sample from a property does not reflect in any way an individual's exposure to lead [25*], with a high degree of variation in both the amount of tap water consumed and the lead concentration present in any given water sample [4*, 32**]. Much more rapid and frequent monitoring of lead in drinking water is required to enable more effective control and understanding of the dynamics of lead release into water for the range of plumbing systems observed across the world. Sequential sampling has been used to understand more about the source of lead in drinking water and to ascertain the effectiveness of lead control strategies [2**]. Citizen science approaches have also been used to enable increased understanding of lead variability, consumer behaviour and more accurate estimation of lead exposure from measurement of drink volumes [4*, 32**]. However, such methods are resource intensive and difficult to implement widely, particularly in resource limited circumstances. Field sampling offers opportunities to gain significant (non-regulatory) information in a quick, inexpensive and reasonably accurate way. The sampling of lead directly in the field can be achieved by sensors that are based on electrochemistry, colorimetry or fluorescence [33]. More than seven commercially available lead field analysers were identified in the review by Dore et al. [33]. However, these methodologies often underestimate particulate lead due to incomplete dissolution during acidification steps. Further developments in lead sensing technology include carbon nanotube electrodes that are able to detect lead down to concentrations of 0.9 μg/L [34] and these have the potential to be produced at low cost by 3D printing [35]. The emergence of sensors that are able to measure lead in the field and even *in situ* will facilitate more widespread sampling. This will be beneficial in a number of different ways:

1) Improved understanding of the dynamics of lead release into water. In turn this will facility improved strategies for remedial actions (pipe replacement, lining and chemical dosing) for the wide range of plumbing systems observed, as well as improve models used to classify lead risk [20*] and provide more evidence to change consumer behaviour.
2) The effectiveness of remedial actions can be more rapidly assessed to determine when water reaches appropriately low lead concentrations.
3) For the control and management of point of use of treatment systems (see below).

4.2 Point of use treatment

Point of use (POU) or point of entry (POE) filtration has gained some traction for control of lead at the point of water consumption. In particular, activated carbon block filtration affords opportunities for removal of both particulate and soluble lead through filtration and adsorption mechanisms, respectively [36]. In a study testing the filters in Flint, 97% of samples returned lead concentrations <0.5 μg/L. Such a strategy allows for universal application in regions where elevated lead concentrations have been identified in drinking water, particularly for vulnerable groups: bottle-fed infants, young children and pregnant woman. Adsorbent systems at a lower technology readiness level are also being tested. For example, graphene oxide aerogels have been developed for removal of soluble lead [37]. However, there are general risks associated with POU treatment processes located in customer premises. This includes evidence of increased microbial concentrations in water released into drinking water from biofilms in POU devices [38, 39]. POU systems for lead control therefore require careful management and maintenance [23] to ensure that microbial and desorption risks are minimised. In addition, such an approach does not address the fact that lead remains in the distribution system and continues to present a risk. Therefore, such devices should only be considered as a short-term interim solution.

4.3 Replacement of all lead pipes and plumbing materials

Many authors note that the eradication of lead from drinking water systems is not feasible in the short-term [40**, 41]. This is largely a factor of cost and convenience, with estimates suggesting that between $2,500-8,000 per household is required for replacement of lead service pipes, in addition to the disruption to the property for installation [42]. To replace all of the lead pipes in the UK has been estimated to be £13.6 billion [12]. However, if we want to truly strive for lead-free drinking water, this must be the ultimate goal for public health practitioners. Costs must be met through a combination of private and public funding mechanisms within a firmer regulatory framework that provides the necessary incentive for positive action. As we have known that lead exposure has significant deleterious effects on the human body since well before the 1960s, it would be a sad dereliction of duty not to target such an outcome so that we are not still concerned about lead in drinking water in 2060.

5. Recommendations

The following is proposed to enable us to meet this objective for eradication of lead and lead-containing materials from our water distribution systems. This requires a number of key aspects to be addressed:

- *Increased testing and improved identification of lead plumbing in water systems.* As has been shown by the recent covid pandemic, frequent and wide scale testing combined with modelling approaches has enabled a much better understanding of threats and has helped engage the public in fighting a public health crisis. As has been noted, our understanding of the extent and location of lead pipes and plumbing is quite poor. Various modelling approaches have been used for identifying risk factors and hotspots for lead in public and private water supplies [20*, 43]. Much broader application of such approaches is required to maximise identification of high-risk residences and communal buildings (such as schools and nurseries), where lead concentrations above action levels are routinely discovered, even in modern buildings [44].
- *More informed consumers on the risks associated with consumption of lead from drinking water.* Studies have shown that consumers have a poor understanding about whether their home is connected to a lead supply pipe or whether their residence contains lead plumbing. For example, research in the US found that between 50-57% did not know these facts [45]. These studies

also highlight racial and social factors that influence the level of concern about lead exposure [46]. Without consumer appreciation of the risks associated with lead exposure, implementation of pipe replacement programmes will not have public will, as well as the inclination, to provide resources to help fund such schemes. This needs to extend to tenants who will inevitably be less informed about property plumbing.

- *A firmer regulatory framework that places an onus on replacement of lead communication, supply pipes and property plumbing.* This could be achieved through mandating lead pipe replacement during selling of homes and residences. Similar schemes should be applied to rental properties, where landlords should be obliged to inform tenants on the plumbing status of the property. Partial replacement of lead pipes can offer only partial benefit [47] or, in fact, increase lead concentrations in water as a result of increasing galvanic connections [26, 48*] and so strong regulatory incentives should be made to enable customer owned pipes to be replaced at the same time as service connections.
- *Current best available treatment for lead control should be applied as universally as possible until pipe and plumbing replacement is achieved.* This includes elevation of water pH and orthophosphate dosing, as well as the prevention of use of leaded solders in plumbing. Where copper alloy fittings are used, these must meet low lead standards. This requires that plumbers understand the importance of minimising lead in water and how this can be achieved. These actions are happening in many parts of the world but monitoring and enforcement is not typically widespread. Improved training,

certification and checking of plumbers and plumbing materials is therefore crucial in meeting these objectives.

6. Conclusions

Lead exposure from drinking water remains a significant public health concern in many parts of the world, primarily as a result of legacy lead plumbing remaining in water supply systems, but also illegal use of lead solder and high lead copper alloy fittings. There are known health impacts associated with human exposure to lead, which has moved health regulators and agencies to recommend that there is no known safe limit of lead exposure. Eradication of lead from drinking water supply systems should be the ultimate goal. However, this requires a stronger regulatory and financial framework to enable this to happen. In the meantime, continued efforts should be focused on ensuring that orthophosphate dosing is applied universally where there is a known risk of lead entering into drinking water. More intensive sampling and monitoring is needed to identify lead hotspots and to understand the dynamics of lead release into drinking water. POU treatment may have an intermediate role to play in removing lead from drinking water, but such devices would require strong monitoring and maintenance programmes to ensure that water consumed from these devices remains safe.

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Highlights

- Lead in drinking water remains a significant problem in many parts of the world
- Regulations are moving towards zero lead concentrations in drinking water
- Complete removal of lead components only way to achieve close to zero lead.
- Improved sampling monitoring and modelling required to identify lead hotspots
- Regulation, funding and public awareness required to stimulate positive action on lead

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: