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A better cost:benefit analysis yields better and fairer results: EPA's lead and copper rule revision

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ABSTRACT

When conducted on a societal level, cost-benefit analysis (CBA) can indicate policies that best allocate scarce public resources. Done incompletely, CBA can produce spurious, biased results. To estimate the potential health benefits of EPA's recent Lead and Copper Drinking Water Rule Revision (LCRR), we used EPA's exposure, compliance, and effect coefficient estimates to monetize 16 of the health endpoints EPA has determined are causally related to lead exposure. In addition, we monetized one health endpoint that EPA has used elsewhere: preterm birth. We estimated that the total annual health benefits of the LCRR greatly exceed EPA's estimated annual costs: $9 billion vs $335 million (2016$). Our benefit estimates greatly exceed EPA's benefit estimates.

There are also nonhealth benefits because lead generally contaminates drinking water through the corrosion of plumbing components that contain lead. The LCRR therefore has 2 components: reducing how corrosive the water is and limited replacement of lead pipes. Reducing corrosion damage to drinking water and wastewater infrastructure and residential appliances that use water yields significant annualized material benefits also: $2–8 billion (2016$). Effectively, the health benefits are free. Finally, while actual exposure data are limited, the available data on lead-contaminated drinking water exhibits known risk patterns, disproportionately burdening low-income and minority populations and women. This economic analysis demonstrates that to maximize national benefits and improve equity, the LCRR should be as rigorous as possible.

1. Introduction

Cost-benefit analysis (CBA) can indicate societally optimally-efficient solutions to best allocate scarce public resources. Done incompletely, CBA can produce spurious, biased results. A good example is EPA's recent Lead and Copper Rule Revision (LCRR)(EPA, 2021).

Drinking water is contaminated by lead through corrosion of plumbing components containing lead, either in the public water distribution system, typically from lead pipes, or private (building) plumbing systems. Consequently, EPA uses 2 tools to control lead contamination of drinking water: corrosion control and limited lead pipe replacement. Implemented together they can significantly reduce water lead levels (WLLs); because of the ubiquity of plumbing components containing lead, neither is adequate alone. Managing corrosion can reduce lead leaching in the short term; lead pipe replacement is necessary for sustained remediation.

EPA's Economic Assessment (EA) accompanying the LCRR contains its assessment of compliance with the LCRR, plus its CBA of the impact of the new rule. We used the EA as the basis for this analysis (EPA, 2020). EPA assessed both costs and benefits against its evaluation of compliance with the existing regulation of lead in drinking water, the 1991 Lead and Copper Rule (LCR).

We have used EPA's assumptions about compliance and costs, as well as the estimated reductions in lead exposures. We differ in including many benefits that EPA omitted including both health and nonhealth endpoints. Relying upon published literature, mostly from EPA documents, we estimated the potential societal benefits omitted from EPA's LCRR and its EA.

For comparability with EPA's estimates, all monetary estimates are converted to 2016 US dollars (2016$) using the Consumer Price Index (CPI) and for medical costs, specifically the medical CPI.

1.1. Background

Lead usually occurs as a corrosion by-product in drinking water, resulting from water's natural corrosivity and lead's extensive use in plumbing components, including pipes, solder, brass and bronze, (Elfland C, Scardina P, 2010) faucets,(Cartier et al., 2012) galvanized steel

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pipe coatings,(Deshommes E, Trueman B, Douglas I, Huggins D, Laroche L, Swertfeger J, Spielmacher A, Gagnon G, 2018) valves and meters. Lead pipes, most commonly the service line connecting the house to the water main in the street, are the major contributors to lead contamination of drinking water; (Agency), n.d.) EPA estimates there are 6–10 million lead pipes remaining in service currently.(Agency), n.d.)(Cornwell et al., 2016) In addition, until banned in 1986, EPA estimated that 98% of US homes had at least some lead solder within the residential plumbing(Levin, 1987). Homes with private wells may be vulnerable to lead leaching from the components of those systems, also(EPA, 1995).

While lead pipes contribute the most lead by volume, the other components are far more numerous. Plumbing components containing lead remain almost ubiquitous in US plumbing, and each can contribute to significant lead exposures. EPA estimates that about one-third of the reductions in WLLs will result from reduced leaching from non-pipe plumbing components containing lead (EA Exhibit 6–14).

In January 2021, EPA revised its 1991 LCR to better control lead and copper contamination of public drinking water.(Environmental Protection Agency (EPA), 2021) The revision, the LCRR, strengthens the regulatory framework on lead in drinking water by limited sampling for lead at schools and child care facilities and providing better information to communities. It also requires better corrosion control treatment (cct) and identification of lead pipes. But very soon after release, EPA announced that it would within 2 years, release the Lead and Copper Rule Improvements (LCRI) to address shortcomings in the LCRR.

Under Executive Order 12,866, issued in 1993, US Federal Agencies must evaluate the costs and benefits of regulations such as the LCRR that will impose costs of over $100 million/year.(Service., 2022) We have used the documents, data, and methods developed and published by EPA to assess the impact of the LCRR.

2. Materials and data

2.1. EPA's anticipated costs of the LCRR

The LCRR imposes costs on community water systems (CWSs) by including water sampling, corrosion control treatment (cct), lead service line (LSL) inventory development and LSL replacement (LSLR), point-of-use installation (POU) in limited circumstances, public education, and outreach among the requirements for compliance. LSL inventory development does not require identifying partial lead pipes, goosenecks or pigtails. LSLR does not include removal of partial lead pipes, goosenecks or pigtails. There is no requirement for replacing all LSLs; indeed, water systems serving under 10,000 have the flexibility to not replace LSLs at all. The data presented in Exhibit 6–14 seem to indicate that EPA expects that under the LCRR over 35 years, only ~530,000 LSLs will be replaced of the ~10 million LSLs estimated currently in service.

To support the LCRR, EPA developed a new variant of its existing SafeWater CBX cost model (EPA, 2020); EPA has used SafeWater CBX in economic analyses to support EPA drinking water rulemakings since the 1997 arsenic proposal. This new model, called SafeWater LCR, incorporates the large degree of variability across water system baseline characteristics that influence utility compliance behaviors and costs related to the LCRR; it has been reviewed both internally and externally. EPA used laboratory and utility data on the baseline number of LSLs, likelihood of replacing LSLs, current cct and/or implementation or improved cct to estimate the changes in baseline and post-treatment WLLs likely to result from the LCRR to estimate its costs.

The LCRR imposes additional costs on the Primacy Agencies that administer state drinking water programs to provide administrative and technical support to CWSs to comply with the LCRR. Also, because the LCRR is expected to result in CWSs using orthophosphate as a corrosion inhibitor, costs related to increased phosphate loadings are estimated, including both the treatment burden for wastewater treatment plants and (unmonetized) ecological damages of increased phosphate loadings to local water bodies. EPA estimated the total annual costs for the LCRR including costs to CWSs, Primacy Aencies and wastewater treatment plants at $335 million (2016$, EA Exhibit 7–2).

2.2. EPA's anticipated benefits of the LCRR

EPA discussed two health benefits in the EA of the LCRR: IQ damage to children associated with decreased lifetime earnings and changes in adult blood lead levels (BLLs). Only 1 health endpoint is monetized: children's IQ decrement-earnings. EPA estimated the total monetized health benefits of the LCRR at $645 (2016$). EPA did not state why other health endpoints were omitted.

2.3. EPA's assessment of lead's health effects

EPA's comprehensive evaluation of lead's health effects, the Integrated Science Assessment for Lead (ISA) (USEPA, 2013) identifies 17 health endpoints causally related to lead exposure (Table 1) plus another 5 health effects that are 'suggestive of a causal relationship'. For monetizing cognitive damage in children and for the qualitative discussions in the EA and the Appendices to the EA, EPA relies on the ISA and the National Toxicology Program (NTP) Assessment of Low-level Lead Effects.(National Institute of Environmental Health Sciences, 2012)

3. Methods

We used EPA's exposure assessments from the LCRR EA (EPA, 2020), from Appendix D to the EA (EPA, 2020), and other EPA publications (EPA, 2018). We have relied upon EPA's assumptions and models for baseline WLLs, the efficacy of cct on WLLs, predicted changes in cct implementation, the likelihood of LSLR, and the effect of LSLR on WLLs; these are presented in EPA's Exhibit 6–14 in the EA(EPA, 2020). Using the Zartarian model for lead intake (Zartarian et al., 2017), EPA estimated the changes to the US population distribution of BLLs that would result from the WLL changes forecast under the LCRR.

The primary intervention in EPA's LCRR is cct, with LSLR as a last resort. Consequently, 2 categories of potential benefits result: materials benefits from reduced corrosion damage to infrastructure and goods, and health benefits from reduced lead exposures that EPA estimates will result from improved cct and limited LSLR. We used EPA's assessment of compliance with the existing LCR as the baseline to estimate both the health and materials benefits likely to result from the LCRR.

We diverged from EPA in two assumptions. First, despite decades of evidence showing that corrosion control mitigates corrosion damage, EPA did not assess any materials benefits from improved cct; we did. Second, EPA assumed there are no health benefits associated with reducing lead exposures in homes without LSLs, despite the presence of numerous other plumbing components likely to contain lead (faucets, lead-soldered copper pipes, brass and bronze connections, etc.) (Elfland et al., 2010), often found even in 'lead-free' plumbing (Ng et al., 2016). Hence, corrosion control will provide health and materials benefits in homes even without lead pipes due to the presence of other potentially lead-containing components. We adhered to EPA's assumption that it can assure effective implementation of the LCRR.

Because the estimated benefits so greatly exceed the costs, we focused on the 'High Cost' scenario as the more stringent of the alternatives EPA considered. We used the average US wage in 2016 ($21/hour) to estimate time losses (SSA, 2022).

3.1. Materials damages

The American Society of Civil Engineers' (ASCE) 2019 Report Card on US infrastructure and the US Department of Transportation (DOT) have assessed corrosion damage to US water infrastructure and structures, including both drinking and waste water systems.(Engineers, 2021))(DOT (Department of DOT (Department of Transportation, 2002)

Table 1
Relating EPA-identified lead health effects to the monetization methods developed in this document.

System	EPA definition	Population	EPA's causality determination	How monetized in EPA's benefit analysis	How monetized in this benefit analysis
Nervous System Effects					
	Cognitive Function Decrements in Children	Children	Causal	IQ earnings	IQ earnings plus short-term costs
	Attention-Related Behavioral Problems in Children	Children	Causal		ADHD
	Conduct Problems in Children and Young Adults	Children & Young Adults	Likely causal		(Included in ADHD)
	Internalizing Behaviors in Children	Children	Likely causal		–
	Auditory Function Decrements in Children	Children	Likely causal		Hearing impairment
	Motor Function Decrements in Children	Children	Likely causal		–
	Cognitive Function Decrements in Adults	Adults	Likely causal		Depression
	Psychopathological Effects in Adults	Adults	Likely causal		ADHD
	Psychopathological Effects in Adults	Adults	Likely causal		Dementia
Cardiovascular Effects (CV)					
	Hypertension	Adults	Causal		Hypertension
	Coronary Heart Disease	Adults	Causal		Coronary heart disease
Immune System Effects					
	Atopic and Inflammatory Responses	Lifetime	Likely causal		) Asthma
	Decreased Host Resistance	Lifetime	Likely causal		)
Hematologic Effects					
	Decreased Red Blood Cell Survival and Function	Lifetime	Causal		) Anemia
	Altered Heme Synthesis	Lifetime	Causal		)
Reproductive and Developmental Effects					
	Development	Lifetime	Causal		–
	Adverse Birth Outcomes	Childhood & life	Suggestive of causality		Preterm birth
	Male Reproductive Function	Adult	Causal		Male reproductive impairment
Cancer					
	Cancer	Adult	Likely causal		Lung cancer
Mortality (cardiovascular)					
		Adult	Causal for CV		Mortality

Together they estimate that corrosion damage in the US totals $72 billion (1998$) annually in direct and indirect costs. In addition, maintenance costs for US drinking systems were $50.2 billion in 2017 (2018$) with over one-third of maintenance costs attributed to corrosion.(Association), 2019) (AWWA, 2019) ASCE estimates $7.6 bil (2018 $) of treated water is lost annually to leaking and broken pipes.(ASCE, 2021)

Appliances that use water are also vulnerable to corrosion. DOT estimated that the corrosion-related costs for water heaters was $460 million annually (1998$), including only replacement, not repairs or labor. We extended their method to estimate the benefits that would result from reduced corrosion damage to residential faucets.

Not all corrosion can be avoided. Commonly, 15–40% of corrosion damage is assumed to be preventable,(Koch G, Varney J, Thompson N, Moghissi O, Gould M, 2016) with a narrower band of likely benefits of 25–35%.(Revie W, 2008)(Koch G., 2017) We used EPA's estimate of how many water systems will require upgrading their treatment and of cct efficacy from EPA's Exhibit 6–14(EPA, 2020). We used the general industry estimate that 25–35% of corrosion damage to appliances is avoidable (ASCE, 2021; DOT, 2002) plus as a sensitivity analysis, EPA's optimistic estimate that 44% is preventable(EPA, 2020).

Because water treatment is water-system-wide and because corrosion damage to infrastructure and appliances is independent of LSL, we ascribe the benefits of reduced corrosion damage to all the residents served by a water system that improves its cct whether there is an LSL or not. Table 2 presents our estimates of materials damage associated with corrosion and Table 7 presents a sensitivity analysis of some key assumptions.

Table 2
Estimated annual materials damage benefits of EPA's LCRR, 2016$.

	Total damage	Avoidable damage	Attributable LCRR water system benefit [a]	Service life	Unit cost	Total benefits from LCRR (mil 2016$)
Avoided water infrastructure damage	$72 bil (1998 $)[b]	25–35%[b]	8–18% of systems			$2122–6684
Avoided water loss	$7.6 bil (2018 $)[c]	25–35%[b]	8–18% of systems			$146-460
Water heaters	$460 mil (1998 $)[b]	5%[b]	8–18% of systems			$2.7–6.1
Faucets	700 mil faucets	25–35%[b]	8–18% of systems	15–20 years[d]	$260 (2021 $)[d]	$158-695
Total benefits						**$2422–7845**

[a] EPA. Economic Analysis for the Final Lead and Copper Rule Revisions. 2020. https://www.regulations.gov/document/EPA-HQ-OW-2017-0300-1769.
[b] Department of Transportation, Federal Highway Administration. 2002. Corrosion Cost and Preventive Strategies in the United States [Summary]. Report FHWA-RD-01-156. Available at https://rosap.ntl.bts.gov/view/dot/39217.
[c] ASCE (American Society of Civil Engineers). 2021 Infrastructure Report Card. Drinking water https://infrastructurereportcard.org/cat-item/drinking-water/#:~:text=Raising%20The%20Grade-,Overview,water%20to%20millions%20of%20people.
[d] Home Insider. How Long Do Faucets Last? https://homeinspectioninsider.com/how-long-do-faucets-last/.

3.2. Health benefits from reduced lead exposures

We used a cost-of-illness approach to monetize many of lead's enumerated health impacts. Costs are annualized and dollars are converted to 2016 US$ for comparability with EPA estimates. Consistent with general practice, costs are discounted at 3%. (Jutkowitz E, Kane RL, Gaugler JE, MacLehose RF, Dowd B, 2017; Reynolds MR, 2014)

Restricted to published literature, we monetized 16 of the health endpoints EPA determined are causally related to lead exposure (Table 1).(EPA, 2013) In addition, we included 1 health endpoint that EPA did not determine was causally related to lead exposure: birth outcomes, which EPA concluded were only suggestive of causality, because EPA included them in an earlier rulemaking.(Kim JJ, Axelrad DA, 2018) To monetize excess mortality, we used EPA's value of a statistical life (VSL).(EPA (Environmental Protection Agency), 2022) Table 3 presents the subcomponents we included to develop our estimates of the unit cost per case.

To develop our incidence estimates, we used the data from EPA's Exhibit 6–14 of the EA on the number of people who would benefit from the LCRR and the reduction in their WLLs. We used EPA's modeled BLLs based on the NHANES data (presented in Exhibit 6–29), and changes in children's BLLs (Exhibit 6–26) and in adult BLLs (Exhibit 6–32) related to the rule. To these we applied the slope coefficients, effect modifiers, etc. that EPA cites in Appendix D to the EA (EPA, 2020) or where EPA's discussion was insufficient to extract a slope coefficient or other risk estimate, we used the NTP analysis, upon which EPA based its assessment.(National Institute of Environmental Health Sciences, 2012)

3.2.1. Nervous system effects

EPA has determined that lead's effect on **children's nervous systems** is causal (USEPA, 2013). We used EPA's estimate of IQ-earnings damage from Exhibit 6–27 that the LCRR will avoid $645 million/year (2016$) in damages to 2.5 million children. To that we added the short-term damages in children associated with cognitive function deficit including compensatory educational support, caretaker demands and social services. To monetize educational costs, we used the average of excess educational costs for US children with learning disabilities. (Chambers JG, Shkolnik J, 2003) Not all children will receive such compensatory services; however, assuming that educational services are efficacious, we assumed that a child who didn't receive such services incurred damages at least equal to the costs. We used the midpoint of 2 estimates of the direct and indirect short-term costs to parents, family and friends of children's cognitive difficulties.(Genereaux D, van Karnebeek CD, 2015)(Stabile M, 2012) We included the out-of-pocket (OOP) estimates from the Medical Expenditure Panel Survey (MEPS) Household Component (HC).(Quality), 2019)

EPA has determined that lead's effects on **attention-related behavioral and conduct problems** in children are causal(USEPA, 2013). We combined those 2 categories and monetized unit costs for Attention Deficit Hyperactivity Disorder (ADHD). We used the midpoint of 2 estimates of the excess medical costs of ADHD. (Chan E, Zhan C, 2002; Doshi JA, Hodgkins P, Kahle J, Sikirica V, Cangelosi MJ, Setyawan J, Erder MH, 2012) Most of the burden of ADHD is behavioral, however, not medical. We used the average from 2 studies of familial economic burdens for a child with ADHD as our estimate of direct productivity effects.(Doshi JA et al., 2012; Zhao et al., 2019) We used Piscitello's assessment of maternal quality of life decrement (Piscitello J et al., 2022) and the MEPS estimate of related OOP. (Quality), 2019)

To avoid double-counting with cognitive damages, we did not include additional educational loss or costs for children with ADHD nor their assessed family economic burden. However, the behaviors of these children often necessitate specialized social and educational services, (Doshi JA et al., 2012) so omitting them may bias results downward.

EPA has determined that lead's effect on **children's internalizing behaviors** is likely causal(USEPA, 2013). (Internalizing behavior includes depressive disorders, anxiety disorders, somatic complaints and teenage suicide.) We did not develop a monetization method for valuing children's excess internalizing behaviors associated with lead exposure.

EPA has determined that lead's effect on **auditory function in children** is likely causal(USEPA, 2013). Hearing impairment has direct health costs and impacts academic performance thereby reducing employment opportunities. We annualized estimated excess lifetime costs for children with hearing loss, including direct medical costs, direct nonmedical costs and productivity loss.(Honeycutt AA et al., 2003) In addition, as a proxy for additional caretaker needs, we added an estimate of the additional caregiver time associated with visual impairment (Köberlein J et al., 2013); to avoid overestimating the costs, we used the lowest category of need. We added the midpoint of 2 estimates of OOP medical expenditures associated with hearing loss. (Foley DM, et al., 2014; Quality), 2019)

EPA has determined that lead's effect on **children's motor functions** is likely causal(USEPA, 2013). We have not monetized that damage.

EPA has determined that lead's effects on **adult cognitive function** are likely causal(USEPA, 2013). Cognitive decline is associated with depression in adults, either as a cause or as an effect and most likely both with a positive feedback loop(Paterniti, S., Verdier-Taillefer, M., Dufouil, C., & Alpérovitch, 2002). We used an estimate of the cost of mild adult depression to value direct medical costs(Levin, 2016). Because 80% of adults with depression reported work, home, and social ramifications, including lower productivity, we included productivity damages associated with mild depression.(Brody DJ, Pratt LA, 2018)

EPA has determined that lead's **psychopathological effect in adults** is likely causal(USEPA, 2013). We used two methods to monetize this damage. First, we used a case of ADHD, a condition that often continues into adulthood.(Doshi JA et al., 2012) Doshi et al. estimated costs to adults with ADHD including excess medical costs, lower productivity and income, lower wages and/or higher unemployment including absenteeism and poorer performance while at work than comparable adults. (Doshi JA et al., 2012) Doshi also estimated excess annual justice system costs for adolescents and adults with ADHD. We added the MEPS estimate for OOP.(Quality), 2019)

An alternative way to monetize lead's **psychopathological effects in adults** is using the costs of dementia. Two studies estimated excess costs related to dementia.(Delavande A et al., 2013; Jutkowitz E et al., 2017) We added the MEPS estimate for OOP. (Quality), 2019)

3.2.2. Cardiovascular system effects

EPA has determined that lead's effect on **hypertension** is causal (USEPA, 2013). We used the American Heart Association (AHA) estimate of annual excess direct medical expenditures of hypertension (Kirkland EB et al., 2018) to which we added OOP estimates from MEPS. (Quality), 2019)

We used estimates of the annual excess per-person productivity burden of hypertension for short-term disability, absenteeism, and presenteeism.(MacLeod KE, et al., 2022) To that we added the estimated nonmonetary productivity losses for absenteeism and for work and home productivity loss combined, controlling for common hypertension comorbidities, including stroke and diabetes.(MacLeod KE, et al., 2022)

EPA has determined that lead's effect on **coronary heart disease** (CHD) is causal (USEPA, 2013). (CHD is also called coronary artery disease or ischemic heart disease.) Again, we used AHA data for average annual per person direct medical costs of CHD.(Virani SS et al., 2022) (The AHA estimate omits expenditures for nursing home care, which may constitute 20–28% of total direct medical costs.(Lloyd-Jones DM, Adams RJ, Brown TM, 2011) For CHD, numerous studies have found that presenteeism loss exceeds absenteeism, i.e., greater productivity losses were attributed to reduced productivity at work, rather than days away from work.(Gordois AL et al., 2016) We added the MEPS estimate for OOP. (Quality), 2019)

Voigt et al. reevaluated the costs of heart failure, concluding that the actual costs are about 5 times greater than estimated by the US

Table 3
Component costs for unit health endpoints.

Body system	EPA component	Population	monetization	Direct Medical Costs	Lifetime costs	Caregiver time	Educational loss/costs	Productivity costs	Family disruption	Other	Out of Pocket Expenses
Nervous System Effects											
	Cognitive Function Decrements	Children	IQ earnings					$22,503 (2016 $)[a] per IQ pt			
	Cognitive Function Decrements	Children	Short-term damages				$5969 1998$[b]		CAD$44,570 (CA 2012$)[c]; $30,500 (2011$)[d]		
	Behavioral & ConductProblems	Children	ADHD	$479 (1996 $)[e]; $621 to $2720 (2010 $)[f]	$321,780 (2015$)[g]	$98,000 – $196,000 (2010$)[h] **lifetime**			$12,188 (2017 $)[i]; $142 to $339 (2010$)[f]		$275[j]
	Internalizing Behaviors	Children	–								
	AuditoryFunction Decrements	Children	Auditory impairment	($23,209 (2000$)[k])	$184,500 (2000$)[k]	5.8 h/wk[l]		($235,279 (2000$))[k]		($67,368 (2000 $))[k, y]	$122 (2012 $)[m]; $187 (2019$)[j]
	Cognitive Function Decrements	Adults	Depression	$14,500 (2014$)[n]				$41,500 (2014 $)[n]			
	Psychopathological Effects	Adults	ADHD	$2120 (2010 $)[f]				$3454 (2010$)[f]	$174 (2010$)[f]	Criminal justice $1973 (2010$)[f]	$275[j]
	Psychopathological Effects (alternative)	Adults	Dementia	Included in lifetime costs	$321,780 (2015$)[g]	Included in lifetime costs			Included in lifetime costs		$5646 (2001 $)[o]
Cardiovascular Effects											
	Hypertension	Adults	Hypertension	$1920 (2016 $)[p]				$344 (2019$)[q]		Nonmonetary time loss[z]	$94[j]
	Coronary Heart Disease	Adults	Coronary heart disease	$12,016 (2015$)[r]				$3033 (2015$)[s]			$208[j]
Immune System Effects											
	Immunological damage	Lifetime	Asthma		$25,000 (1990$) WTP[t]						
Hematologic Effects											
	Decreased Red Blood Cell Survival and Altered Heme Synthesis	Lifetime	Anemia							10% of avg cost of illness in this study	
Reproductive & Developmental Effects											
	Development	Lifetime	–								
	Birth Outcomes	Childhood & life	Preterm birth monetization	See Table 4			See Table 4	See Table 4			$840[j]
	Male Reproductive Function	Adult	Male reproductive impairment	$19,500 (2003$)[u]				43.3 h/yr[v]			$15,000 (2003$)[w]
Cancer											
	Cancer	Adult	Cancer avg	$115,400 (2014$)[n]				$115,400 (2014 $)[n]			Included in direct costs
Mortality											
	All cause	All	vsl							$7.4 mil ($2006)[x]	

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government and AHA estimates (Voigt J, Sasha John M, Taylor A, Krucoff M, Reynolds MR, 2014). Among the omissions identified: Medicare copay of approximately $1000 for an inpatient hospital admission (deductible for Medicare Part A), 20% copay on part B services (inpatient clinician services), and 20% copay for physician services (also part B), based on 2009 costs. Omissions have increased: in 2022 the hospital deductible was $1566. As a sensitivity analysis, we included Voigt's underestimation calculations. However, because hypertension is less severe than heart failure, we used a correction factor of 2.5, half of Voigt's estimation, for the hypertension medical costs (Table 7). We applied the full 5x factor to account for known omissions in CHD cost estimates (Table 7).

3.2.3. *Immune system effects*

EPA has determined that lead's **immunological effect on both decreased host resistance and atopic and inflammatory responses** are likely causal(USEPA, 2013). Because asthma is caused by an overactive immune system, we have used asthma as a proxy for lead's immunotoxicity. As a point estimate for lead's immunological damages, we have used EPA's estimate of the willingness-to-pay (WTP) to avoid a case of asthma for both direct costs and productivity losses of immunological damage.(EPA, 2010a,b) (Kim JJ, Axelrad DA, 2018)

3.2.4. *Hematologic effects*

EPA has determined that lead's **hematologic effect on both decreased red blood cell survival and altered heme synthesis** is causal(USEPA, 2013). We have used a case of anemia as a proxy for both aspects of lead's adverse hematologic damage. Anemia is rarely treated independently and therefore, hard to assess independently. Medical costs for anemic patients are more than double the average. (B. R, 2003; Ershler WB et al., 2005; Nissenson AR et al., 2005) To capture anemia's economic burden, we used 10% of the average per-person costs calculated in this analysis as our point estimate, an approach used previously (Levin, 2016).

3.2.5. *Reproductive and developmental effects*

EPA has determined that lead's effects on **human development** are causal(USEPA, 2013). We could not determine how to monetize all human growth and development. This is a major omission.

EPA has determined that lead's adverse effects on **birth outcomes** are suggestive of causality. We have included these because EPA used them in an earlier rulemaking.(Kim JJ, Axelrad DA, 2018) To value this damage, we used published estimates of the costs of a preterm birth (PTB). PTB is associated with immediate maternal and infant medical costs along with productivity and other costs to the mother, family and friends; higher mortality rates throughout the child's life; and higher risks of many health and developmental problems for the child.(IOM (Institute of Medicine Committee on Understanding Premature Birth and Assuring Healthy Outcomes). 2007., 2007; Rogers LK, 2011) As a basis, we used the assessment of the societal costs of PTB per child by the Institute of Medicine (IOM), updated in 2019.(Waitzman NJ, Jalali A, 2021) The update includes some attributable medical costs to the infant through early childhood and some direct effects associated with 4 conditions associated with prematurity: mental retardation, cerebral palsy, hearing loss, and vision impairment. To that we added EPA's monetization of 4 additional likely sequalae of PTB: asthma, IQ decrements less severe than mental retardation, and early onset of both Type 1 and Type 2 diabetes.(Kim JJ, Axelrad DA, 2018) We added the MEPS estimate for OOP. (Quality), 2019)

There are 2 glaring omissions in the PTB monetization estimate that we could not fill: maternal productivity losses, which for an infant born weeks or even months early can be significant, and excess mortality of PTB infants.

EPA has determined that lead's effects on **male reproductive function** are causal. Because few medical insurance plans cover male fertility treatment, infertile males generally seek treatment outside of traditional reimbursement systems(Dupree, 2016; Meacham RB, et al., 2007). Thus, treatment for male infertility is a burden borne disproportionately by those with private insurance and especially personal financial resources.(Elliott PA et al., 2016) Hence, expenditures are a direct measure of consumers' willingness to pay for treatment. We used the midpoint of the limited data available on the direct medical costs of treatment for male infertility. (Meng MV, Greene KL, 2005) We also included the midpoint of estimates of lost leisure and work time pursuing infertility treatment.(Meacham RB et al., 2007; Wu AK, Elliott P, 2013)

3.2.6. *Carcinogenic effects*

EPA has determined that lead's **carcinogenic effects** are likely causal(USEPA, 2013). Because the International Agency for Research on Cancer (IARC) has classed lead as a Group 2B probable human carcinogen,(Cancer) IARC., 1998) consistent with EPA policy, the health-based Maximum Contaminant Level Goal (MCLG) for lead is zero. We selected a case of lung cancer to characterize these damages. We used the estimate from Levin for the costs of a case of lung cancer, as they are the most complete and recent; they include direct medical costs, productivity and OOP costs(Levin, 2016)(Cipriano LE et al., 2011)

3.2.7. *Excess mortality*

There is evidence of excess mortality associated with lead exposure in infants (Clay K, Troesken W, 2014) and adults.(Lanphear BP et al., 2018) In adults, excess mortality is associated with multiple causes, including cardiovascular disease and cancer,(Weisskopf MG et al., 2009) in both men and women,(Khalil N et al., 2009) and at both high and low exposures. We averaged EPA's risk estimates from Appendix D on cardiovascular damage, monetized by EPA's value of a statistical life (VSL). (EPA (Environmental Protection Agency), 2022) VSLs do not have direct or indirect values.

4. Results

Improved corrosion control produces benefits through reduced damage to public and private water infrastructure and to appliances that use water. The numerous health benefits of reduced lead exposures include 7 body systems and effect everyone – men, women and children. Table 2 presents our estimated annual materials damage benefits and Table 3 presents published estimated annual component health benefits, with sources noted. Table 4 presents PTB estimated component costs. Table 5 summarizes the unit health estimates, converted to 2016$; the incidence estimates; and the total annual health benefits. Table 6 combines the materials and health benefits and compares those to EPA's estimate of the total costs of the LCRR.

Table 7 contains sensitivity analyses probing alternative estimates related to materials damage and health benefits. For materials damages, the general industry estimate of preventable corrosion damage is 25–35%, which is what we used in this analysis. However, in its EA, EPA estimates optimistically that 44% of corrosion damage is avoidable. Using EPA's estimate of avoidable materials damage would increase the benefits by $1864–2063 million/year (2016$). Further, a study identifying omitted costs for heart disease (Voigt et al., 2014) found that actual costs are about 5 times higher than government and AHA estimates. In the sensitivity analysis we used the Voigt estimate of omission (x5) for CHD but for hypertension, which is less severe, we used half the Voigt estimate (x2.5). Together, these would raise the estimated health benefits by $161 million/year (2016$).

5. Discussion

Table 6 summarizes our estimates of the total annual benefit:cost ratio of EPA's LCRR. Relying on EPA's data and analyses, we show that the annual benefits of the LCRR ($11 billion to $17 billion, 2016$) exceed the annual costs ($335 million, 2016$) by 2 orders of magnitude,

Table 4
Estimated cost components of a preterm birth, annualized.

Health endpoint	Subcomponent	Cost (yearUS $)	Source
Medical care infant	Thru age 5	$44,116 (2016$)	Waitzman 2021
Maternal delivery		$5024 (2016 $)	Waitzman 2021
Early intervention services		$1808 (2016 $)	Waitzman 2021
Special education services	For cerebral palsy, intellectual disability, vision impairment	$1604 (2016 $)	Waitzman 2021
Assistive devices		$28 (2016$)	Waitzman 2021
Lost productivity		$12,236 (2016$)	Waitzman 2021
Add'l IQ points lost		$15,884/ point (2014$)	EPA 2018
Asthma		$35,272 (2014$)	EPA 2018
Type 1 diabetes		$199,313 (2014$)	EPA 2018
Type 2 diabetes		$48,508 (2014$)	EPA 2018

EPA 2018. Preterm birth and the benefits of reduced maternal exposure to fine particulate matter. Available at https://www.epa.gov/sites/default/files/2018-06/documents/2018-03.pdf.
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at least 35:1. Even the lowest estimate of materials benefits alone greatly exceeds all the estimated costs of the rule – effectively, the health benefits are free. The results are robust: Benefits exceed costs for each benefit category alone and even eliminating the biggest category of benefits (mortality).

Our economic analysis demonstrates that the US would be better served by a more stringent LCRR that would also increase equity across the US. CBA matters because public health and public policy decisions – and the health of the US population – can depend upon it. To the extent that EPA cannot assure effective implementation of the LCRR, both costs and benefits are decreased. There is no economic justification for EPA to implement less than the most stringent LCRR it has finalized and to ensure that it is implemented as rigorously as possible.

Compliance with the LCR does not ensure that WLLs are safe.(Katner AL et al., 2018)(Stratton SA et al., 2023) EPA published the LCRR in January 2021, and almost immediately agreed to review it soon to address shortcomings through the Lead and Copper Rule Improvements (LCRI).(EPA (Environmental Protection Agency), 2021) EPA identified many needed improvements: proactive and equitable LSLR and replacing all LSLs as quickly as feasible; improving compliance tap sampling requirements to identify locations with elevated WLLs, whether the source is an LSL or other leaded plumbing materials within a residence; strengthening compliance tap sampling to better identify communities most at risk of lead in drinking water and to compel lead reduction actions; prioritizing historically disproportionately impacted communities; and reducing the complexity of the regulation through improvement of the Action and Trigger Level construct. EPA has committed to publishing the LCRI by the end of 2024. Optimistically, EPA commits to evaluating whether some requirements of the LCRR will still be necessary with proactive LSLR efforts and a more protective Action Level.

Table 6
Estimates of the total annual benefits of EPA's LCRR compared to EPA's estimated costs of the LCRR (millions 2016$).

Materials damage avoided	$2422–7845
Health damage avoided	$9248
Total benefits of LCRR	**$11,671–17,094**
EPA's estimated costs of LCRR	**$335**
Benefit:cost ratio	**35:1 to 51:1**
EPA's estimated benefits of LCRR	$645
EPA's benefit:cost ratio	2:1

Table 5
Estimates of the annual health benefits of EPA's LCRR, including the unit costs per specific health outcome, annual incidence and total annual monetized health benefits (millions 2016$).

Body system	Component assessed	Population	Aspect monetized	Monetized unit cost (2016$)	Incidence	Total annual monetized benefit (millions 2016$)
Nervous System Effects						
	Cognitive Function Decrements	Children	IQ earnings	$22,503 per IQ pt	34,000	$645
	Cognitive Function Decrements	Children	Short-term damages	$42,208	5000	$211
	Behavioral & Conduct Problems	Children	ADHD	$10,021	4641	$47
	Auditory Function Decrements	Children	Auditory impairment	$14,999	324	$5
	Internalizing Behaviors	Children	–			
	Cognitive Function Decrements	Adults	Depression	$57,518	480	$28
	Psychopathological Effects	Adults	ADHD	$8972	4000	$36
	Psychopathological Effects (alternative)	Adults	Dementia	$25,072	80	$2
Cardiovascular Effects						
	Hypertension	Adults	Hypertension	$4676	20,000	$94
	Coronary Heart Disease	Adults	Coronary heart disease	$15,958	300	$5
Immune System Effects						
	Immunological damage	Lifetime	Asthma	$45,908	416	$19
Hematologic Effects						
	Decreased Red Blood Cell Survival and Altered Heme Synthesis	Lifetime	Anemia	$3000	10	–
Reproductive & Developmental Effects						
	Development	Lifetime	–			
	Birth Outcomes	Childhood & life	Preterm birth	$73,772	64	$5
	Male Reproductive Function	Adult	Male reproductive impairment	$54,756	160	$9
Cancer						
	Cancer	Adult	Lung cancer	$239,918	1	$0.2
Mortality						
	Cardiovascular	Adult	VSL	$8.85 mil	920	$8142
TOTAL						**$9248**

Table 7
Sensitivity analyses of some annual benefits (million 2016$).[123456]

Benefit category	Component	Subcomponent	Factor used in analysis	Component total estimate	Alternative component estimate	Alternative component total estimate	Difference (2016S mil)
Materials damage	Water infrastructure	Preventable corrosion	25–35%	$2122–6684	44%[1]	$3735–8403	+ $1613–1719
	Avoided water loss	Preventable corrosion	25–35%	$146-460	44%[2]	$257-578	+ $111-118
	Water heaters	Preventable corrosion	25–35%	$3-6	44%[3]	$24-54	+ $21-48
	Faucets	Preventable corrosion	25–35%	$158-695	44%[4]	$277-873	+ $119-178
Health benefits	Hypertension	Omissions	–	$94	x 2.375[5]	$223	+ $129
	Coronary heart disease	Omissions	–	$5	x 4.75[6]	$24	+ $19
Net difference							**+$2012-$2211**

Table 7 presents sensitivity analyses suggesting that the actual benefits could be many times larger. Of these, the only estimate we find overly optimistic is EPA's estimate of avoidable corrosion damage.

5.1. Societal context

The federal requirement to conduct CBA on major rules is designed to ensure that public policy decisions are rational and that precious public resources are used most efficiently. CBA should bring sound science to support the decision-making process(EPA (Environmental Protection Agency), 2010). EPA is aware of myriad health effects causally related to lead exposure (EPA, 2020; USEPA, 2013) but, without explanation monetized only one under the LCRR. EPA has chosen previously to hinge an expensive regulation on limited benefits, and not prevailed(Masur and Posner, 2016).

The perspective of governmental CBA is societal, not individual or local. LSLR is expensive, but there is no ambiguity about the long-term benefits of removing lead pipes. Congress recognized the social importance of LSLR by appropriating $15 billion in dedicated funding in supplemental Drinking Water State Revolving Funds (DWSRF) in the 2021 Bipartisan Infrastructure Law (BIL) (P.L. 117–58) for LSL identification and replacement, provided to states with no match requirement. The BIL also provided $11.7 billion over five years to enhance DWSRF base funding to avoid ambiguity about the intent of the supplemental resources.

The LCRR is more ambiguous. The LCRR does not require water systems to find partial lead pipes, including goosenecks or pigtails, nor does it explicitly call for replacing all LSLs, full vs partial pipe replacement, or locating and removing all lead goosenecks and pigtails (short connecting lead pipes).(Environmental Protection Agency (EPA), 2021) Partial LSLR cannot be used to calculate the rate of LSLR, but is not prohibited despite many studies finding that partial LSLR can increase lead exposures both in the short and long term.(Trueman BF et al., 2016)(Cartier C et al., 2013) Finding and removing LSLs, goosenecks or pigtails remaining on private property is also not required. Indeed, Exhibit 6–14 of EPA's EA suggests that (at most) only about 530,000 LSLs will be replaced over 35 years and demonstrates that at least 7 million US residents could have reduced lead exposures with a stronger LCRR.

While economic analysis can provide valuable insights into setting public priorities, its value depends on the accuracy and comprehensiveness of the cost and benefit estimates. Costs tend to be more thoroughly represented in CBAs due to industry self-interest and relatively-abundant market data(Goodwin, 2019). So, for instance, Chapter 5 of EPA's EA details the economic costs and is 359 pages long. Chapter 6, discussing benefits, totals 56 pages.

The limiting factor is usually incomplete assessment of benefits. Benefits are hard to quantify. (McGartland A et al., 2017; Sunstein CR. 2020., 2020) A review of EPA economic analyses found that 80% excluded entire categories of benefits that the EPA itself described as important because they were 'unquantifiable'(Sinden, 2019). Monetized health benefit estimates are especially sparse. Indeed, Table 3 presenting our estimated monetized health benefits is more conspicuous in the number of empty boxes than in the spaces filled by monetization literature. None of the health endpoints included here is monetized comprehensively – all have significant omissions, indicating that the actual benefits are higher.

However, some practices of CBA mitigate against improving benefit quantification and monetization by, for instance, rejecting combining results derived from different study designs and by setting extremely high standards of 'acceptable' data. That is a self-imposed problem. Omitting data produces biased results. The expected value of uncertainty is certainly not zero. Masur and Posner posit that if a regulator chooses not to monetize all the benefits, it is not a CBA (Masur and Posner, 2016).

5.2. Equity

Lead contamination of drinking water is neither randomly nor equally distributed. It follows known and predictable patterns: minority and low-income communities bear an increased risk of receiving poorer quality drinking water, having higher WLLs and of having lead pipes (Greenway and Gerstenberger, 2010)(Switzer D, 2017)(Fedinick KP, Wu M, 2017)(Landrigan et al., 1999)(Fedinick KP et al., 2019)(Gostin, 2016) Drinking water conditions reflect local conditions and in particular, are heavily determined by local economics. Where communities are less able to pay for LSLR, for enhanced water treatment and for upgrading or even maintaining the water infrastructure, WLLs are likely to be higher. This is true even within communities where less LSLR occurs in poorer parts of town(Baehler KJ, McGraw M, Aquino MJ, Heslin R, McCormick L, 2021). The bias may be intentional or unintentional.(Stratton SA et al., 2023)

Further, there is some evidence that at-risk populations are more susceptible to lead's adverse effects and more likely to have more severe outcomes.(Obeng-Gyasi E et al., 2021) Women in particular, as society's principal caregivers and disproportionately encumbered by domestic responsibilities, bear the brunt of these materials and health damages. (Piscitello J et al., 2022)(Perez, 2019)

A final observation: In its CBA, EPA developed a highly detailed and comprehensive cost analysis while ignoring 95% of the health effects it has determined are causally related to lead exposure. This is also a well-known pattern(Goodwin, 2019).

5.3. Why didn't EPA assess benefits more completely?

EPA's environmental economics research has been at the forefront of US governmental economic research, including benefit monetization, since at least the early 1980's when the authors of this article worked at EPA. EPA's CBA supporting its reduction of lead in gasoline(EPA

Environmental Protection, 1985). monetized components of children's cognitive damage (compensatory education), 4 categories of adult cardiovascular disease (hypertension, heart attacks, strokes and deaths), materials damage benefits (in the form of reduced vehicle maintenance costs) and environmental benefits (of reducing other pollutants through this regulation). The benefits exceeded the costs by billions of 1983$, with a benefit:cost ratio of over 10:1.

In 1986, the economic benefit assessment that led to EPA's decision to reduce lead contamination of drinking water also contained the monetized IQ-earnings metric (the only monetized benefit EPA included in its EA for the LCRR) for children's cognitive damage, as well as the short-term damages of children's cognitive damage (compensatory education), 4 categories of cardiovascular disease (hypertension, heart attacks, strokes and deaths) and the materials damages (reduced corrosion damage) presented in this article(Levin, 1987). The benefits exceeded the costs by almost $1 billion (1985$) and a benefit:cost ratio of 4:1.

EPA's National Center for Environmental Economics (NCEE), under EPA's Office of Research and Development, and EPA's Office of Air and Radiation have continued to monetize health endpoints, although the components have narrowed to include only direct medical costs (but often excluding, for instance, the costs of prescription medicine and outpatient services) and inconsistently, productivity loss estimates. On its website, EPA presents narrowed monetized estimates for asthma (onset and symptom/days), heart attacks, preterm births (included in this article), and numerous other health endpoint components(EPA, 2023)(Kim JJ, Axelrad DA, 2018) NCEE also has the effect coefficients that would have enabled EPA to predict health damages from the data presented in Exhibits 6–26 and 6–32 of the LCRR EA.

With the institutional resources to relate exposures to BLLs, multiple monetized health endpoints, past EPA research evidencing materials damage benefits, and precedent in using these to support major EPA regulations, it is unclear why EPA chose not to include monetized estimates of all the health endpoints EPA has determined are causally linked to lead exposure. This pattern of highly detailed cost estimates and poorly attested health and environmental benefits is, however, also well attested(Goodwin, 2019). (Oreskes N, 2011)(Michaels, 2008)

5.4. Limitations

Data on actual lead exposures from drinking water are sparse, as are data on the effect of cct on WLLs. To support the LCRR, EPA developed a new model that incorporates its own and other laboratory data to predict the outcomes of the LCRR. EPA generally uses the Zartarian model for lead exposure and to predict BLLs, including to support the LCRR(Zartarian et al., 2017). However, subsequent EPA assessments have indicated systemic biases in EPA's lead modeling, in particular, underestimating the impacts of water-lead consumption(Stanek et al., 2020). In particular, Stanek shows that in some age groups, under realistic local and residential water use conditions, drinking water can be the dominant exposure pathway. Thus, EPA's exposure estimates and hence both EPA and our benefit estimates may be significantly underestimated.

The LCRR replaces the LCR promulgated in 1991(*Control of Lead and Copper*, 1991). The LCR required sampling of the first liter of water after a stagnation of at least 6 hours. Because lead from the LSL (if there was one) had not yet reached the tap, this first-flush sample indicates corrosion of plumbing components within the residence.(E Betanzo, 2021) First-flush samples then can be used to estimate the lead contribution of non-LSL plumbing components and the efficacy of cct in the absence of LSL. Publicly available data suggest that in 2016, over 5300 community water systems serving 18 million Americans received water that exceeded the LCR standard of 15 ug/l, which is probably a very low estimate as these were only reported violations.(Fedinick KP, Wu M, 2017) Sampling under the LCR thus may provide a rough 'upper bound' on lead exposures from lead-containing plumbing components other than pipes. These data confirm the Stanek conclusions that residential drinking water can contribute ~10–80% to BLLs(Stanek et al., 2020). These drinking water exposures have clinical significance, ranging from increased fetal deaths in at least one major US city (Edwards, 2014) and risky behavior among teenagers elsewhere(Gibson JM et al., 2022).

Further, EPA underestimated the total benefits of cct because EPA underestimates the total extent of plumbing components containing lead, which include in addition to pipes, solder, brass and bronze, faucets, galvanized steel pipe coatings, valves, meters, and submersible water pumps in residences. Public buildings and especially schools and childcare facilities will also benefit from reduced corrosion and lead contamination.

Other limitations include: Some of the medical cost studies may not reflect the most recent costs. Also, for some health endpoints, we have relied on surrogates of the actual benefits due to data availability. For example, most of the lead-induced cancers are not in the lung, but we used the cost of lung cancer as a surrogate for all of them. We are not sure what the direction of bias is from these choices.

Our estimates are subject to all the limitations of EPA's analysis where we relied on their inputs. Importantly, we have been unable to propagate uncertainty from estimates of the number exposed to estimates of dose-response and number of cases to estimates of costs. Uncertainty is different from bias, however, and we believe our estimates are generally biased low.

5.4.1. Underestimation bias in our analysis

To avoid overestimation, we often used low-bound estimates. Several examples.

1. We omitted 3 health endpoints that EPA determined are causal and 4 that EPA finds are suggestive of causality. For 3 others we used a single estimate for multiple health effects.
2. We only estimated potential corrosion-reduction savings associated with 2 appliances that use water.
3. We used low-bound estimates of the potential efficacy of cct: We used the general industry assumption of 25–35% avoidable damage vs EPA's optimistic assumption that 44% is preventable, and we used an unsubstantiated DOT estimate that only 5% of corrosion damage to water heaters is preventable.
4. We omitted many categories of health costs, such as special education needs for children with ADHD or hearing impairment; most estimates of caretaker time, productivity losses, oop, etc. No single health endpoint is complete.
5. Where possible, we use the lowest category of services.
6. The biggest single down-bias is likely omitting an estimate of increased all-cause mortality.

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6. Conclusion

The evidence that the benefits of implementing the LCRR exceed the costs is overwhelming. To achieve even the modest benefits EPA has predicted, EPA must implement the most rigorous LCRR it has finalized and ensure that it is implemented as rigorously as possible, including using its full enforcement authority.

EPA's upcoming LCRI is intended to provide proactive and equitable LSLR, compliance tap sampling that better identifies communities most at risk of lead in drinking water, compel lead reduction actions and improve compliance. We hope EPA can implement such changes. Lead contamination of drinking water has been the weakest link in EPA's lead remediation efforts for almost 50 years.(Fedinick KP et al., 2019) (Baehler KJ, McGraw M, Aquino MJ, Heslin R, McCormick L, 2021) (Young and Nichols, 2016)(Gostin, 2016) It is time for EPA to take the lead.

Author contributions

Ronnie Levin: Conceptualization, Data curation; Formal analysis; Investigation; Methodology; Project administration; Visualization; Writing – original draft; Writing – review & editing. Total 80%. Joel Schwartz: Data curation; Formal analysis; Methodology; Software; Validation; Writing – review & editing. Total 20%

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Declaration of competing interest

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