The attributable annual health costs of U.S. occupational lead poisoning

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Background: U.S. occupational lead standards have not changed for decades, while knowledge about lead's health effects has grown substantially.
Objective: The objective of this analysis was twofold: to estimate the attributable annual societal costs of health damages associated with occupationally lead-exposed U.S. workers and, more broadly, to develop methods for a fuller valuation of health damages.
Methods: I combined data voluntarily reported to NIOSH on the number of highly exposed workers with published literature on the health effects of lead in adults to estimate the potential health benefits of lowering the U.S. occupational limit. I developed simple algorithms for monetizing more fully both the direct medical and indirect (productivity) damages associated with those high lead exposures.
Results: I estimated direct medical costs of $141 million (2014US$) per year for 16 categories of health endpoints, and combined direct and indirect costs of over $392 million (2014US$) per year for the 10,000 or so U.S. workers with high occupational lead exposures.
Conclusions: Reducing allowable occupational lead limits produces annual societal benefits of almost $40,000 per highly exposed worker. Given underreporting of actual exposures and the omission of important health effects, this is likely a severe underestimate.

Keywords: Lead exposure, Occupational exposures, Occupational attributable health costs, Costs of illness

Introduction

Fortunately, as evidence of lead's toxicity has emerged at lower and lower exposure levels, U.S. blood lead levels (BLLs) have declined over the past 40 years, and mean levels in both children and adults are now approximately 1.5 μg/dl.[1,2] A glaring exception is among individuals occupationally exposed to lead. U.S. occupational standards have not changed in over 35 years, permitting workers to continue to be exposed to lead at levels that are a danger to themselves and their families, especially their children. Parental occupational lead exposure has been a known risk for elevated BLLs in children for 150 years and across a range of occupations[3–6] with case histories going back to 1860.[7,8]

The 1978 (U.S.) Occupational Safety and Health Administration (OSHA) standards require medical surveillance of workers occupationally exposed to lead. Workers must be removed from lead exposure when BLLs exceed 50 μg/dl for construction workers or 60 μg/dl for general industry workers (averaged over the previous 6 months). The workers may return to work when BLLs ≤40 μg/dl.

In 2008, U.S. Environmental Protection Agency (EPA) reduced the national air quality limits for lead to 0.15 microgram per cubic meter of air (μg/m^3) to protect public health, while the federal *occupational* standard remains at 50 (μg/m^3).[9] And in 2012, the National Institute of Environmental Health Sciences (NIEHS) concluded that BLLs <10 μg/dl can interfere with biochemical events in cells throughout the body and are associated with cascading adverse health effects in adults, across multiple body systems, including the reproductive, developmental, neurological (central and peripheral), immune, cardiovascular, and renal systems, as well as metabolic and other disruptions at cellular and subcellular levels.[10] In consonance with NIEHS, in 2013 the California Department of Public Health determined that BLLs of 5–10 μg/dl posed a health risk to working adults and recommended that CA occupational regulations be revised to better protect workers.[11,12] The same year, EPA in its Integrated Scientific Assessment of Lead summarized the health literature as indicating health effects in adults at levels of 5 μg/dl and possibly lower.[13] Finally, in 2015, the National Institute of Occupational Safety and Health (NIOSH) designated 5 μg/dl as its reference blood lead level.[14] These recent reviews support a reappraisal of the lead exposure levels that may be safely tolerated in the workplace for either short or extended periods.

Evaluating the efficacy of revising OSHA's standard necessitates assessing the attributable social costs of high occupational lead exposures. Workers' compensation (WC) systems are poorly suited to capture chronic illnesses

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or health endpoints that may appear after employment ends. And contrary to popular press alleging considerable fraudulent WC claims,[15] extensive data document that a high percentage of occupational illnesses and injuries never enter the WC system.[16,17] Indeed, WC claims have declined by more than half since the early 1990s while occupational injuries and illnesses rates have remained at best constant.[18]

Employers have disincentives, financial and other, to report work-related illness or injury,[16,19,20] including to avoid increasing their workers' compensation costs, social, and insurance-related incentives for presenting low injury rates, poor recordkeeping, restrictive workers' compensation reforms,[21] concern about winning contracts,[22] and similar; for instance, a recent survey found that 90% of employers did not comply with OSHA recordkeeping regulations.[23] Among workers, fears include being fired or disciplined, that their co-workers might suffer under safety-based incentive programs and the bureaucratic process of applying for workers' compensation.[20] Consequently, compensable and insurance costs routinely (and severely) underestimate both occurrence and costs.

Previous valuations of lead medical costs have focused principally on children, with the exception of lead's cardiovascular effects. EPA's regulations of lead in gasoline and lead in drinking water included children's medical costs, the costs of compensatory education, and reduced lifetime earnings associated with IQ damage, using a cost-of-illness (COI) approach coupled with value of a statistical life (VSL) that has since served as the template for regulatory impact analyses for EPA and other governmental agencies.[24,25] Direct medical costs focused on expenditures for formal medical services.

Schwartz's seminal article laid the conceptual foundation for monetizing the panoply of costs imposed on *society* by health damages to *individuals*.[26] However, methods for monetizing social benefits were not developed, and attention was instead focused on children. Gould,[27] Muennig,[28] and Reyes[29] extended the categories considered in valuing children's health damages but did not expand the COI approach beyond expenditures for formal medical services, for instance, to include deductibles, out-of-pocket expenditures, time lost, and incidental costs associated with obtaining medical services and costs of informal medical services. For children's health effects, omitting the costs of caretaker time is enormous.

For adults, the EPA COI analyses only included the costs of cardiovascular disease (CVD) calculated through estimates of expenditures for formal medical services plus lost work time.[24,25] Again, a very narrow range of the direct costs of CVD health damage was included, and only CVD-related mortality was included. Currently, there are no methods to combine the pieces to monetize completely either the direct (medical and personal) or indirect (productivity and personal) losses and costs to the worker, family, employer, and society.

The objective of this analysis is twofold, one substantive and the other methodological. First, I wanted to estimate the attributable annual societal health and economic benefits that could accrue from reducing U.S. occupational lead exposures to below 30 μg/dl for the approximately 10,000 U.S. workers who remain occupationally exposed to lead. In addition to the more commonly included costs of formal medical services, I present estimates of annual direct medical costs for 16 categories of health damages, across 7 body systems, that include, for example, consideration of out-of-pocket expenses, compensation for underestimation resulting from Medicare expenditure data, omitted drug costs and the costs of informal care, increases in general medical costs associated with certain conditions (e.g. depression), and the burden of comorbidities.

Second, for the purposes of applied risk assessment, I developed methodologies and algorithms to aggregate disparate components to capture more completely the attributable societal health and economic benefits of specific health conditions. My methods provide a framework within which assessments of components of COI studies can be combined to provide a fuller monetization of health damages. As methods and research improve, these methodologies are amenable to expansion.

Methods and data

Approach

Illness and injury impose costs on the affected individual, family, care providers, the employer, and society at large. Table 1 presents the components of a full COI assessment.

I have used a COI or human capital approach to valuing health damage, which posits direct and indirect cost categories. To value mortality, I used a VSL based upon willingness-to-pay studies. This combined approach follows EPA's guidelines.[30] However, because no single data repository contains all of the information necessary to fully characterize the costs of any health condition, it is necessary to draw upon a multitude of disparate data sources.[31] The most commonly published COI studies present the most easily obtained data: Medicare, Medicaid, and WC expenditures; and hospitalization costs; which, of course, contain only a fraction of the full cost of the illness.

All costs have been converted to 2014$ using the medical component of the Consumer Product Index.

Direct medical costs are associated with diagnosis, treatment, rehabilitation, and accommodation including medical and other care provided at the work place, in a medical facility, and at home. Payers include Medicare and Medicaid, private insurance, federal and state workmen's compensation, employers, patients and their families, and other public and private entities. Transportation (to and from), parking, over-the-counter medicines, and such, associated with medical services are also direct costs, although rarely included. In general, I accepted calculated direct medical costs as published, assessing what components were included in the analysis (hospitalization,

Table 1 Cost components of illness/injury

	At work	At service delivery site		At home
		Inpatient (includes both general & specialty)	*Outpatient* (includes both general & specialty)	
Direct medical costs	Health unit, including staff, treatment, equipment, supplies & services; co-workers & supervisors	Hospitalization		Trained & untrained care providers, including transportation
	Transportation, (ambulance or driver, transport & parking)	Treatment & tests	Treatment & tests	
	Out of pocket expenditures (copays & deductibles, phone calls, record keeping, etc.)	Specialist provider services	Medical & specialist provider visits	
		Transportation (ambulance or driver, transport & parking)	Transportation (ambulance or driver, transport & parking)	
		Pharmaceuticals (prescribed & over the counter)	Pharmaceuticals (prescribed & over the counter)	Pharmaceuticals (prescribed & over the counter)
		Specialized consumer goods (e.g. pillows, clothing, food, etc.)	Specialized consumer goods (e.g. pillows, clothing, food, etc.)	Specialized consumer goods (e.g. pillows, clothing, food, etc.)
		Out of pocket expenditures (copays & deductibles, phone calls, record keeping, etc.)	Out of pocket expenditures (copays & deductibles, phone calls, record keeping, etc.)	Out of pocket expenditures (copays & deductibles, phone calls, record keeping, etc.)
		Costs to family & friends	Costs to family & friends	Costs to family & friends
Indirect costs	Lost work (costs to employer & employee), includes absenteeism & presenteeism	Time loss associated with inpatient care	Time loss associated with outpatient care	Lost home production
	Impositions on supervisor, colleagues, etc.			Lost leisure
	Avoidance activities			Avoidance activities
	Decreased future earnings, including e.g. moving from full- to part-time work			Specialized consumer goods (pillows, clothing, food, etc.)
	Specialized consumer goods (chair, clothing, food, etc.)			Costs to family & friends
	Costs to co-workers			

outpatient services, pharmaceuticals, and the like), and compensating for key omitted elements with other published estimates.

Expenditure studies generally cover only money transfers, omitting deductibles, copays, service delivery, existing services, personal and family care, and the like. Many Medicare expenditure studies omit Part D (pharmaceutical) costs.[32,33] Medicare and Medicaid often pay much less than private insurers for comparable services;[34–36] in this analysis, I have assumed Medicare expenditures are about 1/3 less than private insurers. And, while employers pay more for comparable services than government programs, they pay less than the government overall due to limitations on the coverage they provide.[37] In the American Health Policy Institute study,[37] employers overall paid less than half of what government programs paid for a covered person. Consequently, in this analysis, I have assumed employer expenditures are 1/3 of actual (direct) medical costs.

Out-of-pocket medical costs (deductibles, coinsurance, copayments, and personal expenditures for covered services plus all costs for uncovered services) are omitted in many studies, despite evidence that patients are incurring increasing burdens of medical costs;[33,38,39] e.g. out-of-pocket medical expenses can exceed 20% of health costs for lung cancer patients. The Affordable Care Act "metal" plans (Bronze, Silver, Gold, Platinum) pay an estimated 60–90% of health costs with the remainder covered by other sources, most often the patient.[40] In 2010, Medicare beneficiaries spent on average $4,734 ($5,267 in 2014$) of their own money to purchase health services, including premiums for Medicare and other types of supplemental insurance; women pay more than men, and older patients pay more than younger.[39] Overall, the Medical Expenditure Panel Survey (MEPS) has estimated that personal out-of-pocket medical expenditures are 14.6% of total U.S. medical expenditures.[41]

Minimal components of monetized medical costs: I considered two components to constitute the minimal elements of a COI assessment: *Delineated direct medical costs* of diagnosis and treatment, including hospitalization, in-patient and out-patient medical services, drugs, and similar; which are generally at least partly covered by insurance or reimbursement programs; and *out-of-pocket expenditures*, described above and which are by definition uncompensated.

In addition, significant costs are associated with delineated medical costs that are omitted entirely, such as transportation to-from, parking, food, and other incidental costs while in treatment, informal care, waiting time, recovery/recuperation times, and the like. These associated costs are not generally covered by insurance nor are they included in COI studies, and I could not find any published estimates for them. But ignoring them does not make them go away.

Indirect costs include productivity and personal time loss for the individual (including the family) and the employer (i.e. lost national output, not just workers' lost take-home pay).[16,42] Productivity losses include both absenteeism and presenteeism (at work, but with diminished productivity due to the condition). Personal time loss includes leisure time lost; forced changes in personal habits, such as averting behaviors; physical limitations; an unwanted change in work schedule; and many others.[43] Payers include Social Security, disability, and private insurance, federal and state workmen's comp, employers, and patients. Indirect costs also include specialized consumer products related to the condition, such as pillows, chairs, food, clothing, and the like. Indirect costs are harder to identify and quantify than direct costs.

Health effects included and valuation methodologies

The data on lead's adverse health effects are substantial. Effects reported to be "causal," "suggestive," or "likely causal" in EPA's ISA[13] or Kosnett[44] are included here, with the concentration-response assessment from the ISA. In consonance with EPA's practices, I assumed that medical treatments are efficacious, and that those who do not receive medical services incur costs at least as great as the cost of the treatment.[24,25]

Studies of severe depression, dementia, and kidney failure mention that *informal health care* at home is common, but valuing it is omitted from the assessments. In such instances, I added four hours/month at the 2014 average wage, i.e. $23/hour,[45] increasing the annual direct medical unit estimate by $4,800 for each of those cases.

Neurotoxicity: I monetized seven aspects of lead's damage to the nervous system: sensory effects including muscular pain and ocular disorders, and psychopathological effects including depression (mild and severe), panic disorders, nervous system disorders, and dementia. As indicative of a nervous system disorder, I used data on the costs of Parkinson's disease.

Numerous analyses show that self-reported *musculoskeletal pain* predicts a statistically significant long-term increase in general use of health care services in both the primary and the secondary health care sectors,[46] although the direct medical costs of musculoskeletal pain are relatively low.[47] The greater impact is an increase in other medical costs: for instance, Yelin[47] found that average costs for those reporting musculoskeletal conditions were double for those who did not, but across a wide spectrum of medical services. Yelin controlled for all comorbidities, but because musculoskeletal pain may be indicative of other conditions, this may introduce a downward bias. To value musculoskeletal pain, I added the MEPS[41] estimate of personal medical expenditures (7.5%) to the Yelin estimate.

Eye damage also has relatively low direct medical costs but is associated with increased general medical service use;[33,48] similarly, both are associated with the risk of depression. Visual impairment also imposes costs in terms of informal care needs, estimated at 2 days/year.[48] I did two computations to value eye damage. First, I combined the direct medical costs estimated by Frick, and added the costs of two days of care and the personal expenditures from MEPS[41] (18.9%). I also used the data from the Javitt[32] Medicare costs analysis, compensated for using Medicare expenditures, and added the costs of medicines and the personal expenditure estimate from MEPS. Because the two valuations produced an estimate that differed by less than $1700, I used the mid-point of the two methods.

For *depression*, again the direct mental health medical costs were less than the increase in general medical care, but compounded by low reporting: Only 29% of those experiencing depression (39% with severe depression) contacted a mental health professional.[49] The ratio of costs of all medical services for depressed to non-depressed patients was 1.5–2.9, with differences in median annual non-mental health outpatient, pharmaceutical and in-patient costs.[50] For this analysis, I used the Luppa *et al*.[51] estimate range of direct mental health costs and added the MEPS[41] estimate of out-of-pocket costs (18%) and the estimate range from Welch[50] of the additional non-mental health medical costs. Because both Luppa and Welch presented ranges, I used the low-low estimate for mild depression and the high-high estimate for severe depression.

I used the direct medical cost estimates from Shirneshan *et al*.[52] to value *panic disorders* and added the out-of-pocket estimates from MEPS.[41] The result is very similar to the estimate using Stuhldreher *et al.*[53]

To indicate the costs of *nervous system disorders*, I used data on Parkinson's disease as a surrogate. Parkinson's is associated with relatively high pharmaceutical costs, both directly related to Parkinson's and across other medical areas;[54] frequent comorbidities; and increased likelihood of living in a long-term care facility.

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I used the mid-point of Hurd *et al.*[55] and the Alzheimer's Association's estimates[56] of the direct care costs to value *dementia*. But because each study has important omissions (Hurd omitted Medigap payments, copayments, deductibles, and other costs) and the Alzheimer's Association estimate is based on payments, I compensated by adding their estimates of personal out-of-pocket expenses (22 and 21%, respectively). In addition, numerous studies indicate that informal care is required at home, so I included four hours/month at the average U.S. wage.[45]

Using data from the Alzheimer's Association that the longest stage is "moderate," with shorter early and severe stages, I assumed half of dementia sufferers (with milder symptoms) would remain at home but that half would require a residential setting.[57]

Reproductive effects: Costs of reproductive damage include costs through delivery, costs through futility (cessation), and/or – because of increased neonatal needs associated with fertility treatment babies – additional costs through infancy (and beyond); unfortunately, such estimates do not exist. For male infertility, I did not include any costs associated with a live delivery; for females, I estimated 15% live births[58,59] (see notes to Table 2). For both males and females, I used the out-of-pocket estimates from Wu *et al.*[60]

The estimate for preterm births includes excess delivery and neonatal (through the birth year) costs.[61] I applied the overall average out-of-pocket estimate from MEPS[41] (14.6%) of all conditions for a preterm birth; this is likely low.

Kidney disease: I monetized chronic kidney disease (CKD) and End Stage Renal Disease (ESRD). CKD is a notoriously silent disease, with under 10% awareness of those with Stages 1–3;[62] I assumed that those who are unaware incur damages at least equal to the costs of treatment. To value both ESRD and CKD, I used the Medicare expenditure data from the U.S. Renal Data System; because USRDS[63] includes Part D (pharmaceutical costs) while the 2014 assessment does not, I used USRDS 2012. These estimates are very similar to those using data from the Kidney and Urologic Diseases Information Clearinghouse.[64] Cubanski *et al.*[39] assessed out-of-pocket expenses for ESRD at 15%, while MEPS[41] estimated 5.4%; I used the mid-point of the two estimates for ESRD and the lower (MEPS) estimate for CKD.

Lung cancer: EPA's estimate of the cost of lung cancer[65] ($38,569 in 96$) is similar to Cipriano *et al.*[33] ($80,979 in 06$) – $75,980 vs. $104,500 (14$); neither included pharma costs. I used the mid-point of those estimates, and included pharma cost estimates from Van Houtven *et al.*[66] For out-of-pocket expenses, I used the mid-point of MEPS[41] (5.4%) and Cipriano *et al.*[33] (average about 15%); Cipriano documented that patient liability costs have been steadily rising since the early 1990s.

Cardiovascular disease (CVD): I monetized hypertension and myocardial infarctions. I used data from the American Heart Association[67] to estimate costs for *hypertension*. However, Voigt *et al.*[68] assessed the underestimation in the AHA data, which included restricted diagnostic codes; omitting non-hospital care, out-of-pocket costs, etc.; and concluded that actual medical costs were 1.8–3.2 times greater than the AHA estimates. I used the mid-point of the Voigt data (2.5) to address some of the downward bias in the AHA data. However, Voigt also omitted some out-of-pocket direct medical costs (such as transportation and parking, over-the-counter drugs, and other); to avoid double counting, I included only half of the MEPS[41] estimate for personal medical expenditures for hypertension: 10.3%.

To estimate the costs of a *heart attack*, I used three studies,[69–71] each of which covered a component: Ben-Joseph and Afana estimated immediate Medicare hospital costs for the first 30 days after an MI, and NBER estimated the cost to health insurers for the first 90 days after a heart attack. Assuming that these early costs are the highest and that costs for the rest of the year are lower, I assumed these peaks constituted 2/3 of the annual medical costs for a heart attack. I added the MEPS 2012 estimated out-of-pocket direct medical costs for heart conditions (6.8%),[41] and compensated for using Medicare and health insurer expenditure data.

Comorbidities: Because of lead's cascading effects within the body, several conditions occur commonly as comorbidities: hypertension and CVD, anemia, depression, and other psychopathological conditions. Of these, depression has the most significant costs and anemia has the most significant health damage, considering both morbidity and mortality.[72,73] Using the excess cost of anemia (which can easily double the medical costs of other conditions)[74,75] to indicate the potential costs for comorbidities, I added the average cost of all the morbidities estimated in this paper as a proxy for the systemic disruptions manifesting as different clinical and subclinical comorbidities resulting from high lead exposures.

Excess mortality: I did not monetize health endpoints resulting in death.

Table 2 presents the estimated monetized health endpoints, tracking the inputs to the final estimate.

Indirect cost methods and estimates

Indirect costs can equal,[76] exceed,[77,78] or be less than[79,80] direct medical costs, with a range of over an order of magnitude depending on the method, disease, and comprehensiveness of the study. Similarly, in applied risk

Table 2 Monetized annual health endpoint unit estimates, with sources noted

System	Subcomponent	Delineated Medical Costs (yr$)	Source	Comprehensiveness	Adjustment (Source)	Out of Pocket (source)	Total medical unit costs (2014$)
Cardiovascular	Hypertension	$550 (2010$)	AHA 14[67]	Restricted diagnoses, Medicare expenditures	Voigt 14 (×2.5)[68]	10.3% (half of MEPS 12)[41]	$1700
	Myocardial infarct	$38501 (1996$)	NBER[71]; Afana[70]; Ben-Joseph[69]	Only first 90 days insurer expenditure & Medicare	×1.5 to acct for rest of yr; ×1.5 to acct for insurer exp vs. all med	$7500 (midpt of CDC 11[99] & ACS 13)[114]	$116000
Neurologic	Muscular pain	$3578 (1996$)	Yelin 01[47]	Only expenditures	×1.5 to acct for exp vs. all med	7.5% (MEPS 12)[41]	$11000
	Ocular disorder	$3105 plus 2 days informal care (2002$); $345 + $2193 (2003$)	Frick 07[48]; Javitt 07[32]	Javitt is Medicare, no part D	×1.5 to acct for Medicare exp vs. all med + 12% for Part D	18.9% (MEPS 12)[41]	$7000
	Depression – mild	$1000 (2003$)	Luppa 07[51]	Also increases general medical costs	+ $2120 (Welch 09)[50]	18% (MEPS 12)[41]	$4000
	Depression – severe	$2500 (2003$)	Luppa 07[51]	Also increases general medical costs	+ $20574 (Welch 09)[50]; added $4,800 for informal care	18% (MEPS 12)[41]	$25000
	Nervous syst disorder	$10349 (2002$);$11167 (02$)	Huse 05[32]; Noyes 06[54]			$3345 (02$, Noyes 06)[54]	$22000
	Panic disorder	$1658 (2009$)	Shirneshan 13[52]			18% (MEPS 12)[41]	$2200
	Dementia	$29000 (2010$)	Avg of Hurd 13[55]; Alzheimers Assoc 14[56]	Excl informal care	Added $4,800 for informal care	21% (Alz Assoc)[56]	$63000
Reproductive	Fertility damages male	$19500 (2003$)	Meng 05[115]	Excl live delivery		$5338 (13$,Wu 14)[60]	$35000
	Fertility damages fem	[a]	Unit costs fr Neumann 94[58] (92$), Goldfarb 96 (92$)[59], Pratt 04 (03$)[116]	Excl live delivery	Assume 15% live delivery	$5338 (13$,Wu 14)[60]	$101000
	Preterm birth	$103938 (05$)	Behrman & Butler 07[61]			14.6% (MEPS 12)[41]	$161000
Kidney disease	ESRD	$79916 (10$)	2012 USRDS[63]	Medicare expenditures	X 1.5 to acct for just expenditures; added $4,800 for informal care	midpoint of 15% (Cubanski 39) and 5.4% (MEPS 12)	$144000
	Chronic kidney disease	$13395 (10$)	2012 USRDS[63] for those 50–64	Medicare expenditures	X 1.5 to acct for just expenditures	5.4% (MEPS 12)[41]	$23500
Carcinogenicity	Lung cancer	$38569 (96$), $80979 (2006$)	EPA 97,[65] Cipriano 11[33]	Medicare exp, coinsurance & deduct/copay; no pharma	+ 16% pharma (Van Houtven 04)[66]	5.4% (MEPS 12),[41] 15% (Cipriano 11)[33]	$115400
Mortality	Value of a statistical life	$7.4 mil (06$)	EPA 14[30]				NA
Anemia as comorbidity		Avg cost of illness in this analysis $56000		Anemia can double the cost (Smith,[74] Nissenson[75])			$56000

Note: Used unit treatment costs from Neumann[58], Goldfarb[59] and Pratt[116], plus excess medical estimates from Behrman & Butler[61].
Sources: Refs. [114–116].
[a]Neumann 1994 $55–212,000 (92$), plus NICU costs $10–100,000 (92$), 12% success rate.

assessments, using very narrow definitions of both direct (just inpatient costs) and indirect (paid work time lost), direct: indirect costs vary over an order of magnitude depending upon the age of the person, from 10:1 to 1:1.1.[81] Conversely, OSHA provides an e-tool to estimate indirect costs that assumes direct: indirect costs range from 1:1.1 to 1:4.5, with higher ratios at lower levels of medical costs.[82]

Several health conditions have disproportionate impacts on personal time or are associated with significantly decreased productivity and/or participation in the work force[83]: musculoskeletal pain,[84–86] depression,[51,84] panic disorder,[53,87] nervous system disorder,[53,89] and fertility disruption for both males and females.[90] In these cases, I used data from the specific studies to estimate indirect costs. In the absence of data to the contrary (eight cases within this analysis), as a (mid) point estimate, I assumed that indirect (productivity and personal time loss, and employer non-medical) costs equal direct (medical) costs, probing this with sensitivity analyses for indirect:direct costs of 0.5:1 and 2:1 (Table 6).

Neurological damage: For valuing the indirect costs of *musculoskeletal pain*, indirect costs exceed direct medical costs.[85] Presenteeism (diminished productivity) exceeds absenteeism[84] and is also associated with increased accidents.[86] Pain also results in fear and voluntary guarded movement resulting in muscle disuse and deconditioning. Stewart[84] found that on average, workers who lost productive time lost ~5.5 h/week, of which 1.2 h/week was absence and 4.3 h/week, presenteeism. NIOSH found that workers in pain lost an average of 8 days/year exclusively due to pain.[91] Because indirect costs also include personal time loss and reduced home production, I used the estimates of work loss as an indication of personal time loss. I valued the indirect costs at the 2014 average wage rates from the BLS.

Studies of the burden of *depression* also show that indirect costs greatly exceed direct costs.[50,51,83,91] Again, presenteeism (diminished productivity) exceeds absenteeism.[49,92] I used the mid-point range of estimates (2–3:1) to value mild versus severe depression. It should be noted, however, that analyses based on observed data found much higher effects: for instance, Valenstain found that patients with depression missed an average of 4.8 workdays and suffered 11.5 days of reduced productivity in a 3-month period;[93] extrapolating to a full year yields a productivity loss of 19.2 days of absenteeism and 46 days of presenteeism. Weighting by central tendency values in this instance may result in an underestimate of costs. Again, because indirect costs also include personal time loss, reduced home production, etc., I assumed the estimates of work loss indicate personal time loss. I valued the indirect costs through the 2014 average wage rates from the BLS.

All social anxiety disorders, such as *panic disorders*, are associated with relatively low direct costs but much higher indirect costs.[53] Panic disorders result in absenteeism and reduced productivity, as well as social avoidance and often irrational behaviors related to avoidant decisions.[88] I used the Stuhldreher[53] estimate that indirect costs are triple direct medical costs for social anxiety disorders such as panic attacks.

Nervous system disorders such as Parkinson's disease have high indirect:direct costs.[88,94] I converted the estimates

Table 3 Monetized unit estimates of annual indirect costs and total annual (medical and indirect) costs (2014$)

System	Subcomponent	Estimated unit medical costs	Estimation basis of indirect costs	Estimated unit indirect costs	Total unit costs
Cardiovascular	Hypertension	$1,700	Direct = indirect	$1,700	$3,400
	Myocardial infarct	$116,000	Direct = indirect	$116,000	$232,000
Neurologic	Muscular pain	$11,000	Stewart [84]; Indir:dir is 3–4:1 (Stewart 03[84], Carlson 11,[85] Letvak 12[86])	$24,000	$35,000
	Ocular disorder	$7,000	Direct = indirect	$7,000	$14,000
	Depression – mild	$4,000	Indir is ×2 (midpt of Welch[50], Greenberg[92] & Stuhldreher[53])	$8,000	$12,000
	Depression – severe	$25,000	Indir is ×3 (Stewart 03[84], Greenberg[92] & avg of others)	$75,000	$100,000
	Nervous system disorder	$22,000	Noyes 06[54]; Whetten-Goldstein 97[88]; Rubenstein[89]	$43,500	$65,500
	Panic disorder	$2,200	Indir is ×3 (Pittig 14[87], Stuhldreher 14[53])	$6,600	$8,800
	Dementia	$63,000	Direct = indirect	$63,000	$126,000
Reproductive	Fertility damages male	$35,000	Indir has added time loss (Wu[90])	$37,000	$72,000
	Fertility damages fem	$101,000	Indir has added time loss (Wu[90])	$103,000	$204,000
	Preterm birth	$161,000	Time loss is mom's losses	$163,000	$324,000
Kidney disease	ESRD	$144,000	Direct = indirect	$144,000	$288,000
	Chronic kidney disease	$23,500	Direct = indirect	$23,500	$47,000
Carcinogenicity	Lung cancer	$115,400	Direct = indirect	$115,400	$230,800
Mortality	Value of a statistical life	NA	NA	NA	$9 mil
Anemia as comorbidity		$56,000	Direct = indirect	$56,000	$112,000

from Whetten-Goldstein[88] as the indirect estimate, which is very similar to the ratio of 3:1 from Stuhldreher[53] and others.

Reproductive damage: Wu[90] found that the time loss associated with fertility issues was significant, both for men and women. I added their estimate (83.3 h/year) to the estimated medical costs to approximate indirect costs.

Indirect costs associated with *preterm births* are associated with the mother.

Mortality: A death valued through VSL has neither direct nor indirect costs.

Table 3 presents my annual direct medical cost estimates plus the estimated indirect costs for the health effects that I monetized, including the inputs.

Mortality valuation

Excess mortality: I used EPA's value of a statistical life.[31] A VSL estimates how much people are willing to pay for small reductions in their risks of dying from adverse health conditions. I combined the VSL estimate, based on a willingness to pay approach, with the COI estimates based on EPA guidelines for regulatory impact analyses and applied risk assessments.[31] To probe the marginal impact of using EPA's relatively high estimate of a VSL ($9 million), I conducted a sensitivity analysis reducing the valuation per death to $1 million (Table 6).

Exposure data

Estimating the number of occupationally lead-exposed workers

Through the Adult Blood Lead Epidemiology and Surveillance (ABLES) program, NIOSH collects data on lead levels ≥10 μg/dl in U.S. adults (residents and non-residents) from laboratories in 25–40 states; the variability in reporting rates may relate to changes in funding levels. Based on those data, the rate of adults with lead levels ≥25 μg/dl declined from 14.0 per 100,000 employed adults in 1994 to 7–8 during 2004–2010 and was ~ 6 in 2011–2012.[95] Of the estimated 10,000 adults with BLLs ≥25 μg/dl, NIOSH estimates that 95% are work-related exposures. Laboratories participate voluntarily in ABLES and report their own data. As the only estimate of highly exposed U.S. workers, it serves as the basis in this analysis.

Estimating how many workers will incur health damages

For calculating the number of workers suffering specific health damages, I used existing effect slopes, where possible, assuming BLLs will be reduced to 30 μg/dl or below. I have assumed that the changed standard would apply to all workers, so the attributable fraction is 100%.

I defined *severe renal disease* as a glomerular filtration rate (GFR) below 30, and estimated the change in the population prevalence assuming the mean is shifted downward by 20 ml/min following reduced lead exposure, based on the slope in Akesson,[96] applied to the GFR distribution in the adult population from the Third National Health and Nutrition Evaluation Survey (NHANES III).[97] Using methods from Navas-Acien[98] who studied a population with mean BLL of 1.58 μg/dL, the change in prevalence of severe kidney disease in the worker population is predicted to be 2.4%, or 260 fewer cases. I assumed half would incur CKD and half would suffer from ESRD; I tested the impact of more conservative distributions in a sensitivity analysis (Table 6).

For *myocardial infarction*, I estimated the effect of reduced BLLs using the results of Jain.[99] With a BLL reduction from about 45 μg/dl to about 30 μg/dl, the hazard ratio is 0.86 and the expected baseline rate (based on CDC data[100]) is 58. Hence, with a lower lead exposure, we would expect eight fewer events per year. Because in Jain[99] 84% of the events were non-fatal, to avoid double counting with mortality benefits (below) I estimate six fewer non-fatal events.

For *hypertension*, Cheng[101] reported an association of bone lead with the incidence of hypertension; I used the equation of Behinaein[102] to convert between bone lead and blood lead. Assuming a baseline prevalence of hypertension among workers of 20%,[103] lower lead exposure would decrease hypertension by 5%, resulting in 550 fewer cases.

To estimate the increase in excess (*all-cause) mortality* associated with elevated lead exposures, I used the results of Weisskopf.[104] I scaled the log hazard ratio between their second and third tertile by the ratio of the estimated decrease in patella lead (estimated at 13.5 μg/g using Behinaein[102]) to the difference in the mean patella lead between the two higher categories in Weisskopf[104] to get a linear extrapolation of the dose response, producing a hazard ratio of 0.81 if the exposure was at the lower level. I estimated the baseline mortality rate using CDC data[100] for that age group, yielding an estimate of 10 fewer deaths per year from all causes resulting from lower lead exposures.

For *fertility damage*, I used results from Zhu[105] who found a continuous relationship between birth weight and maternal lead levels in a population with low BLL (mean 2.1 μg/dl). Although my cost estimates have assumed a 15% live delivery rate for fertility treatment, I have not included that in the estimate of preterm births, to avoid double counting.

When the data are inadequate to support calculating an effect slope, I assumed:

- If effects are evident at 25 μg/dl,[13,44] 1% of the exposed population would evidence it;
- If effects are evident at 20 μg/dl,[13,44] 2% of the exposed population would evidence it;
- If effects are evident at 10 μg/dl,[13,44] 3% of the exposed population would evidence it; and
- if effects are evident at 5 μg/dl,[13,44] 5% of the exposed population would evidence it.

Estimating an occupational exposure of 1–3% is common.[106]

Table 4 Exposure estimates, based upon NIOSH estimates of lead-exposed workers

System	Subcomponent	Exposure estimate (%)	Exposure estimate (calculated)	Number of workers
Cardiovascular	Hypertension		550	550
	Myocardial infarct		6	6
Neurologic	Muscular pain	2		200
	Ocular disorder	0.5		50
	Depression – mild	2.5		250
	Depression – severe	2.5		250
	Nervous syst disorder	1		100
	Panic disorder	1		100
	Dementia	5		500
Reproductive	Fertility damages male	3		300
	Fertility damages fem	3		300
	Preterm birth	1		100
Kidney disease	ESRD		130	130
	Chronic kidney disease		130	130
Carcinogenicity	Lung cancer	1		100
Mortality	Statistical life		10	10
Anemia as comorbidity		1		100

Table 5 Total estimated annual attributable health-related damages associated with lead exposure of U.S. workers (thousands 2014$)

System	Subcomponent	Exposure estimate	Total estimated medical costs	Total estimated indirect costs	Total
Cardiovascular	Hypertension	550	$935	$935	$1,870
	Myocardial infarct	6	$696	$696	$1,392
Neurologic	Muscular pain	200	$2,200	$4,800	$7,000
	Ocular disorder	50	$350	$350	$700
	Depression – mild	250	$1,000	$2,000	$3,000
	Depression – severe	250	$6,250	$18,750	$25,000
	Nervous system disorder	100	$2,200	$4,350	$6,550
	Panic disorder	100	$220	$660	$880
	Dementia	500	$31,500	$31,500	$63,000
Reproductive	Fertility damages male	300	$10,500	$11,100	$21,600
	Fertility damages fem	300	$30,300	$30,900	$61,200
	Preterm birth	100	$16,100	$16,300	$32,400
Kidney disease	ESRD	130	$18,720	$18,720	$37,440
	Chronic kidney disease	130	$3,055	$3,055	$6,110
Carcinogenicity	Lung cancer	100	$11,540	$11,540	$23,080
Mortality	Value of a statistical life	10	NA	NA	$90,000
Anemia as comorbidity		100	$5,600	$5,600	$11,200
Totals			**$141,160**	**$161,256**	**$392,422**

There are a few exceptions: cancer, ocular damage, and general nervous system disorders. For *cancer*, the estimated slope in the published literature is shallow, only two target organs (lung and stomach) have been identified, and the overall occurrence is low. For *general nervous system and panic disorders*, again, the overall occurrence is low. In these cases, I assumed only a 1% effect. For *ocular damage*, given the scarcity of data, I assumed only 0.5% effect. Finally, for using the excess costs of anemia as a surrogate for all the comorbidities, because of the uncertainties about double counting, I also only assumed a 1% effect.

On the other hand, the increasing evidence for higher risk of dementia and depression led me to estimate a 5% effect level, and for reproductive effects, I assumed 3%. To avoid over counting, I assumed that only 1% of live births would be disrupted.

Table 4 presents the exposure estimates.

Results

Table 5 combines the monetization and exposure estimates. I rounded the estimates to account for uncertainties in both the data and the methods. The largest single contributor to the total is the valuation of all-cause mortality ($9 million/case), although only 10 cases are predicted. On a per unit basis, the next most expensive medical costs are preterm birth ($161,000), ESRD ($144,000), heart attacks ($116,000), and lung cancer ($115,400). As indirect costs are based upon direct medical costs in

Table 6 Sensitivity analyses (millions 2014$)

	Total direct medical costs	Total indirect costs	Mortality valuation	Total-total annual estimate
Baseline defaults	$141	$161	$90	$392
Default assumption indirect costs = 0.5 direct[a]	$141	$117 (−27%)	$90	$348 (−11%)
Default assumption indirect costs = 2 × direct[a]	$141	$270 (+67%)	$90	$519 (+32%)
Default assumption death = $1 million	$141	$161	$10	$310 (−20%)
Default assumption less:more severe is 2:1 for renal disease & depression	$134 (−5%)	$151 (−6%)	$90	$375 (−4%)

[a]Default assumptions used for eight health endpoints.

this analysis, these categories remain the highest total costs, as well.

For total costs (direct and indirect times exposure), dementia, female reproductive effects, and death from all causes are highest.

Sensitivity analyses

I conducted sensitivity analyses on three defaults with potentially important impacts on the results: the relationship of indirect costs to direct medical costs, the valuation of mortality, and for renal disease and depression, the distribution between more and less severe forms.

(1) Testing the influence of the default assumption that in the absence of data to the contrary (8 endpoints), indirect costs equal direct medical costs: total annual indirect cost estimates ranged from $117 million to $270 million (−27 to +67%, Table 6) as the default was changed from 1:1 to 0.5:1 or 2:1. Total medical plus indirect cost estimates changed from $348 million to $519 million (−11 to +32%).
(2) Reducing the valuation of mortality from $9 million to $1 million reduced the total-total to $310 million (−20%, Table 6).
(3) Changing the assumption of the distribution between more and less severe forms of renal disease and depression from 1:1 to 1:2 reduced medical costs by about $7 million (almost 5%), indirect costs by almost $11 million (about 6%) and the total-total about $17 million (about 4%) (Table 6).

Because I thought a correlation between the assumptions regarding indirect costs, the valuation of a death, and the distribution of condition severity was unlikely, I conducted the analyses independently.

Discussion

The objective of this analysis was twofold: to estimate the attributable annual social costs of health damages associated with occupationally lead-exposed U.S. workers and, more broadly, to develop methods applicable across numerous assessments for a fuller monetization of particular health damages.

My approach is oriented to the public policy risk managers who determine U.S. public health policy, including environmental and occupational exposures. The methods – combining data from multiple sources, including COI studies with VSL – reflect the applied risk assessment framework used routinely within the federal government, articulated by EPA.[30]

I estimate that the annual attributable direct medical damages of current high occupational lead exposures in the U.S. are about $141 million and the combined direct and indirect costs are over $392 million. Sensitivity analyses of three defaults with potentially important impacts showed the robustness of the results.

So, who bears the burden of this estimated $392 million each year? Workers themselves pay a high fraction: from 18[41] to 44%[106] of the direct costs, and likely more of the indirect costs (up to 90% of lost income[107]). Taxpayers, through Medicare, Medicaid, Social Security, and other governmental resources, pay approximately 20%.[106] In addition, employers, consumers and all workers absorb costs in the forms of lower profits, higher prices, and lower wages.[105] Schools pay for the cognitive damage to workers' children from take-home exposures.

The aging of the U.S. population, especially the U.S. work force, will increase these costs as age is a common risk factor. The U.S. Census Bureau estimates that the number of people over 65 will almost double between 2012 and 2050. Only two of these health endpoints are likely to be fatal in the short run: lung cancer and ESRD. (And even here, survivorship rates have increased over the past few decades.[108,109]) This will further burden the working population that will have to support the elderly.

Limitations

This analysis blends cost estimates from a range of published studies using varied methods, health outcomes, years, and purposes. I combined them in an attempt to characterize as completely as possible the annual medical and personal damages attributable to high lead exposures. Uncertainties and errors are associated with each study and compounded by aggregation. In addition, taking components from different data-sets introduces error because they represent different populations. I call on subsequent researchers to refine these methods. However, valuing uncertainties at zero is an untenable approach to public health.

The largest uncertainty is the number of U.S. workers occupationally exposed to lead. The NIOSH ABLES program collects voluntary, self-reported data, and is widely assumed to underestimate actual exposures. The 27 states that most often report to NIOSH contain approximately 60% of the U.S. population; extrapolating from the reporting states suggests that nationwide about 15,000 workers are exposed to lead at work. Leigh *et al*. estimated further that comparing the ABLES data to BLS Annual Survey data suggests that 51% of occupationally exposed workers are not reported, even after extrapolating the reported data to non-reporting states.[106] More significantly, CA DPH reported that of the principal lead-using industries in California, only 87% of battery manufacturers, 56% of non-ferrous foundries, 14% of radiator repair entities, 8% of painting companies, and only 1% of wrecking and demolition companies were testing their workers; no construction companies reported lead exposures.[10] To add context, the U.S. Census Bureau estimated that there were 710,000 construction establishments in 2002 with 7.2 million employees.[110] Finally, EPA conservatively estimated that up to 394,365 business entities would need to be certified to conduct lead paint repairs and renovations in residences built before 1978;[111] as of May 2015 only 128,000 were registered.[112] The full extent of under-reporting occupational lead exposure is impossible to assess, but it is likely that actual worker lead exposure is at least double and possibly an order of magnitude (or more) greater than the ABLES data attest.

Omitting take-home exposure and damages to workers' children severely underestimates the attributable costs of occupational lead exposure.

The relationship between direct and indirect costs is unknown. In sensitivity analyses changing the default assumption of the ratio of indirect to direct costs from 1:1, to 0.5:1 and 2:1, the results remained robust with none changing the estimated total by more than 11–32%.

EPA's VSL estimate is higher than some other estimates, although it is used widely in regulatory impact analyses within the U.S. Government. A sensitivity analysis using a mortality valuation of $1 million reduced the total to $310 million (−20%, Table 6).

This analysis underestimates employers' costs, which are greater and more varied than generally perceived. They include the costs of hiring and training replacements for injured workers, productivity impacts on co-workers including compensated and uncompensated work redistribution, "hidden" administrative and supervisory time devoted to consequences of the injury or illness, redundant hiring as insurance against downtime resulting from injury or illness, productivity impacts related to deteriorated morale and labor relations, and a host of other burdens.[16,42]

Finally, I have omitted many health damages associated with high lead exposures, such as cognitive and hearing decrements and metabolic changes. I also omitted valuation for pain and suffering, decreased quality of life, and similar. In addition, family and social relationships suffer and family members frequently sustain significant and uncompensated economic and psychological hardships.[113] Ignoring these unassessed costs will not make them go away.

Conclusion

This is probably a very low estimate of the actual annual costs of high lead occupational exposures in the U.S., and should be understood as merely indicative of the potential benefits of reducing those exposures. At almost $40,000 per exposed worker as a lower bound estimate, cost effective controls are possible.

Abbreviation

μg/dl micrograms of lead per deciliter of blood, the standard measure of recent lead exposure

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