Journal of Occupational and Environmental Hygiene, 8: 520–532
ISSN: 1545-9624 print / 1545-9632 online

DOI: 10.1080/15459624.2011.601710

Review: Lead Exposure in Battery Manufacturing and Recycling in Developing Countries and Among Children in Nearby Communities

Perry Gottesfeld[1] and Amod K. Pokhrel[2]

[1]Occupational Knowledge International, San Francisco, California
[2]School of Public Health, University of California, Berkeley, California

The battery industry is the largest consumer of lead, using an estimated 80% of the global lead production. The industry is also rapidly expanding in emerging market countries. A review of published literature on exposures from lead-acid battery manufacturing and recycling plants in developing countries was conducted. The review included studies from 37 countries published from 1993 to 2010 and excluded facilities in developed countries, such as the United States and those in Western Europe, except for providing comparisons to reported findings. The average worker blood lead level (BLL) in developing countries was 47 μg/dL in battery manufacturing plants and 64 μg/dL in recycling facilities. Airborne lead concentrations reported in battery plants in developing countries averaged 367 μg/m^3, which is 7-fold greater than the U.S. Occupational Safety and Health Administration's 50 μg/m^3 permissible exposure limit. The geometric mean BLL of children residing near battery plants in developing countries was 19 μg/dL, which is about 13-fold greater than the levels observed among children in the United States. The blood lead and airborne lead exposure concentrations for battery workers were substantially higher in developing countries than in the United States. This disparity may worsen due to rapid growth in lead-acid battery manufacturing and recycling operations worldwide. Given the lack of regulatory and enforcement capacity in most developing countries, third-party certification programs may be the only viable option to improve conditions.

Keywords battery, blood lead level, developing countries, lead, recycling, third-party certification

Correspondence to: Perry Gottsfeld, Occupational Knowledge International, 4444 Geary Blvd., Suite 300, San Francisco, CA 94118; e-mail: pgottesfeld@okinternational.org.

INTRODUCTION

Lead poisoning remains a significant occupational disease and a ubiquitous environmental health threat to children. Lead causes numerous adverse health effects, including damage to the nervous system, the kidneys, the cardiovascular system, the hematopoietic system, and the reproductive system.(1–8) In children, blood lead concentration is associated with a significant decrease in academic performance and lower standardized test scores (including IQ test scores) and is linked with hyperactive and violent behavior.(9) The International Agency for Research on Cancer (IARC) has classified lead and inorganic lead compounds in Group 2A as probable human carcinogens.(10)

Occupational and environmental lead exposure in the developing world arguably may have a more profound effect than in developed countries. Poor nutrition, common in developing countries, increases lead absorption through the gastrointestinal tract.(11) Lead poisoning imposes a range of hidden costs on developing countries. One study estimated that a 50% decrease in childhood blood lead levels in Nigeria could save the country \$1 billion annually; the health care cost of lead exposure for adults is estimated to total \$7 billion.(12) Lead-induced decrements to health status may further decrease productivity, which will lead to less investment and the continuation of the cycle of poverty.(13)

The Lead Battery Industry

The battery industry is the principal consumer of lead and uses an estimated 80% of annual primary lead (mined) and secondary lead (recycled) production.(14) Approximately 50% of global lead production is derived from recycling lead batteries.(15) These batteries are used primarily in vehicles for starting, lighting, and ignition purposes, but are also used in photovoltaic solar installations and telecommunications systems to store energy. In developing countries where the power supplies are often inconsistent, lead batteries are routinely used in homes and businesses to back up computer systems, lights, and appliances when outages occur. Electric vehicles are becoming an important market for lead batteries; electric bikes in China presently account for more than 20% of the country's lead demand.(16,17) The expected increase in automobile, solar, telecommunications, and computer sales in the developing world will increase the production and recycling of lead batteries.

It is estimated that between 60,000 and 70,000 people are employed globally in lead battery manufacturing, in addition to a similar number working in mining, smelting, and refining.(15) The vast majority of these workers live in the developing world. The efficiency of lead recovery from battery recycling can vary greatly, and the crude methods employed in most developing countries result in the release of millions of tons of lead into the environment.(18) The Basel Convention, which came into force in 1992, restricts the export of used lead batteries to developing countries where environmentally sound recycling cannot be ensured. The United States exports a substantial number of used lead batteries to Mexico, South Korea, India, and other countries, which underlines the importance of investigating lead exposures in these countries.(19,20)

Given forecasts that the lead battery industry will double in size in many developing countries over the next 5 to 10 years, we performed this review of lead exposures among workers in lead battery manufacturing and recycling and among children living in nearby communities.(21–23) We discuss barriers and opportunities to better control these exposures and environmental emissions.

METHODS

We reviewed the published literature on lead exposures due to lead-acid battery manufacturing and recycling operations (which include reconditioning used batteries) in developing countries. We used the terms "lead, blood lead levels (BLLs), battery manufacturing, recycling, and children," and searched databases of the National Library of Medicine, MEDLINE service, and Web of Science and Global Health. More than 232 studies appeared on these search terms, among which 98 were relevant for this review. Pertinent references cited in the identified studies were also reviewed.

We limited our review to studies with an abstract published in English from 1993 to 2010 and excluded facilities from our search if they were located in countries considered "developed," (Table I). Information on relevant measures from developed countries was used to compare aggregate results obtained in this review. Given the improving economies in many countries during this time period and the lack of a universal classification system, we used the term "developing countries" to distinguish the latter from the "developed countries" listed in Table I. We used the 1993 start point for three reasons. First, there are few pertinent studies prior to 1993. Second, similar manufacturing technologies have been employed around the world since 1993. Third, the start point follows the implementation of the Basel Convention mentioned previously.

From the 98 selected studies identified in our search, 84 provided summary measures of BLLs (the arithmetic mean, geometric mean, or median) among exposed worker cohorts and, in some cases, airborne lead concentration inside the plants. Ten studies reported summary measures of BLLs in children living in the vicinity of battery manufacturing and recycling facilities. We attempted to contact the authors of studies that presented incomplete statistics (e.g., only the range of BLLs) and did not provide a summary cohort exposure.(24–31) If no additional information could be obtained, we excluded the study.

TABLE I. List of Developed Countries Excluded from the Literature Search

Region	Countries
Europe	Andorra
	Austria
	Belgium
	Denmark
	Finland
	France
	Germany
	Iceland
	Ireland
	Italy
	Liechtenstein
	Luxembourg
	Monaco
	Netherlands
	Northern Ireland
	Norway
	Scotland
	Spain
	Sweden
	Switzerland
	United Kingdom
North America	Canada
	United States
Oceania	Australia
	New Zealand
Asia	Japan

For the BLL data, we grouped those studies reporting the arithmetic mean BLL and grouped separately those studies reporting either the geometric mean or median BLL. For individual studies that reported separate arithmetic mean BLLs for two or more subgroups, we computed an average value weighted by the number fraction in each subgroup. For individual studies that reported a geometric mean (GM) and a geometric standard deviation (GSD) for the BLLs, we estimated the cohort arithmetic unweighted mean (μ) by the equation: $\mu = \text{GM} \times \exp[0.5 \times (\ln \text{GSD})^2]$.(32) Because the distribution of BLLs tends to be right skewed, we judged that the GM BLL was approximately equal to the median BLL and therefore grouped studies reporting only the GM with those reporting only the median value.(33) For each group, we calculated the mean or median of all the individual study values in the group.

We evaluated the BLL trend from 1993 to 2010 among the 61 studies that reported arithmetic mean BLLs by regressing the individual study results against the year of study publication. Blood lead level samples were almost certainly collected before the publication dates listed in the tables. The Theil-Sen median slope for trend in Stata software (version 10; StataCorp LLC, College Station, Texas) was used to evaluate these cohort BLLs over time.(34) This statistical analysis is a nonparametric estimate of slope, identified as the Kendall-Theil slope (also known as the Kendall-Sen).(34–36) The method is resistant to the effects of outliers and non-normality in residuals, as commonly observed in BLL data.(37) We also used the Student's t-test to compare average BLLs among lead battery plant workers reported in the period 1993–2002 versus the period 2003–2010. We chose 2002/2003 as the cut point to divide the data set into approximately equal numbers of BLL reports. Five countries, accounting for 40 of the studies, were represented in both groups allowing for comparisons over these time periods.

RESULTS

Table II lists arithmetic mean BLLs among workers at lead battery plants in 20 countries as reported in 61 studies; a total of 8350 workers are represented in the table. Arithmetic mean cohort values ranged from 22 to 128 μg/dL, and the mean and median of the 61 cohort arithmetic mean values are 47 μg/dL and 42 μg/dL, respectively. Table III lists median BLLs among workers at 12 lead battery plants in six countries as reported in seven studies; a total of 1189 workers are represented in the table. The median of the cohort median values is 37 μg/dL. Table IV lists arithmetic mean BLLs among workers at 14 lead battery recycling/reconditioning plants in 13 countries as reported in 13 studies; a total of 479 workers are represented in the table. Arithmetic mean cohort levels range from 43 to 113 μg/dL, and the mean and median of the cohort arithmetic mean values are 64 μg/dL and 60 μg/dL, respectively.

Table V lists the arithmetic mean or GM value for lead concentrations in air (based on area and personal samples) in 12 battery manufacturing plants, and the arithmetic mean lead concentration in air (based on area samples) in one battery recycling facility. One study that summarized airborne lead exposure in Chinese lead battery industries was excluded because of discrepancies in the results.(38) Due to the lack of detail regarding workplace conditions associated with the samples in most studies, we combined the area and personal sample results within the same industry. Arithmetic mean airborne lead concentrations ranged from 39 to 1260 μg/m^3, and geometric mean airborne lead concentrations ranged from 33 to 355 μg/m^3. Among the studies that provided an arithmetic mean airborne lead concentration, the average and median value of the eight means are 367 μg/m^3 and 264 μg/m^3, respectively. Among the six studies that provided a GM airborne lead concentration, the median value of the five GMs is 103 μg/m^3.

Table VI lists 10 studies that reported the arithmetic mean or median BLLs for groups of children residing near lead battery manufacturing and recycling plants in developing countries; a total of 2284 children are represented in the table. These studies included different age ranges (up to 15 years) and distances from the subject plants (0.18 to 5 km). The arithmetic mean BLL in groups of children range from 9 to 71 μg/dL; the average and median values of the nine group arithmetic means are 29 μg/dL and 19 μg/dL. Reported median BLLs for two other groups of children were 7.3 and 8.1 μg/dL.

As seen in Figure 1, there appears to be a modest decline in worker BLLs during the period 1993 to 2010, although the trend is not statistically significant (Theil-Sen median slope = –0.69, with two-sided 95% confidence interval [–1.54; 0.16]). When the cohort arithmetic mean BLLs are grouped by publication date with 2002/2003 as the cut point, the group average BLL is higher during 1993–2002 (50 μg/dL) than during 2003–2010 (44 μg/dL), although the difference is not statistically significant ($p = 0.29$ for a two-tailed test).

DISCUSSION

Tables II–IV demonstrate that lead battery industry workers in developing countries, at both the front and back end of the battery life cycle, experience BLLs that far exceed health protection guidelines. Based on a comprehensive review of lead toxicity in adults, Kosnett et al.(1) recommended that individuals be removed from occupational lead exposure if a single blood lead concentration exceeds 30 μg/dL, or if two successive blood lead concentrations measured over a 4-week interval are $\geq$ 20 μg/dL. The ACGIH® has established a biological exposure index of 30 μg/dL.(39) The Centers for Disease Control and Prevention (CDC) recommends that BLLs should be maintained at $<$ 5 μg/dL for occupationally exposed women who are or may become pregnant.(40)

BLLs among U.S. and U.K. workers in lead battery manufacturing facilities are substantially lower than the levels reported in this review.(41–43) Although no comprehensive U.S. occupational lead registry exists, several states have compiled extensive data on BLLs from workers in the lead battery industry via laboratory reporting requirements. In California, BLLs above 25 μg/dL must be reported to the state. In practice, most blood lead test results (at all levels) are voluntarily reported. In 1999 (the last year that data was reported), among 1931 workers from this industry, no reported worker BLLs exceeded 60 μg/dL, and only 36 (1.9%) worker BLLs exceeded 40 μg/dL.(44) From 1993 through 2001 in Washington State, only five workers from the lead battery manufacturing industry reported BLLs exceeding 60 μg/dL.(45)

The U.S. National Institute for Occupational Safety and Health (NIOSH) had compiled BLL report data for 2007 from states that collect and summarize laboratory testing reports. Among 1743 production workers in storage battery industries (NAICS 335911) in California, Iowa, and Oregon, 325 (18.6%) had BLLs $\geq$ 25 μg/dL, and 21 (1.2%) had reported BLLs $\geq$ 40 μg/dL (personal communication from Walter A. Alarcon,

TABLE II. Arithmetic Mean BLLs of Workers in Lead Battery Manufacturing Plants

Year	Author	Country	n	Arithmetic Mean BLL (μg/dL)
1993	Zhang(70)	China	128	125.7[A]
1993	Far et al.(71)	Singapore	25	48.9
1994	Ibiebele(52)	Barbados	20	35.3
1994	Makino et al.(72)	Philippines	199	64.5
1994	Singh et al.(73)	India	15	52.0
1995	Kim et al.(74)	South Korea	66	45.7
1995	Schwartz, S. et al.(75)	South Korea	308	29.1
1996	Solliway et al.(76)	Israel	34	40.7
1996	Cordeiro et al.(77)	Brazil	20	49.4
1996	Chang et al.(78)	Taiwan	27	48.6
1997	Lai et al.(79)	Taiwan	219	56.9
1997	Yucesoy et al.(80)	Turkey	20	59.4
1997	Schwartz et al.(81)	South Korea	57	25.4
1997	Kuo et al.(82)	Taiwan	5	43.6
1998	Ho et al.(83)	Singapore	50	32.5
1998	Ehrlich et al.(84)	South Africa	382	53.5
1998	Vaglenov et al.(85)	Bulgaria	22	60.9[A]
1998	Williams et al.(86)	Trinidad-West Indies	22	23.0
1998	Undeger and Basaran(87)	Turkey	25	74.8
1999	Froom et al.(88)	Israel	94	38.1
1999	Chuang et al.(63)	Taiwan	392	23.9
2000	Caldeira et al.(89)	Brazil	17	63.8
2000	Restrepo et al.(90)	Colombia	43	98.5
2000	Roh et al.(91)	South Korea	49	42.6
2000	Basaran and Undeger (92)	Turkey	25	74.8
2000	Ratzon et al.(93)	Israel	63	42.5
2000	Chuang et al.(94)	Taiwan	206	31.8
2001	Duydu et al.(95)	Turkey	31	36.3
2001	Vaglenov et al.(96)	Bulgaria	103	55.9[A]
2002	Hwang(97)	Taiwan	96	29.6
2002	Wang et al.(53)	Taiwan	229	58.6[B]
2002	Sonmez et al.(98)	Turkey	13	25.3
2003	Mishra et al.(99)	India	34	128.1
2003	Nusier et al.(29)	Jordan	83	51.4
2003	Palus et al.(100)	Poland	44	50.4
2003	Suzen et al.(101)	Turkey	71	34.5
2003	Pizent et al.(102)	Croatia	143	41.4
2003	Duydu and Suzen(103)	Turkey	71	34.5
2003	Lormphongs et al.(104)	Thailand	182	21.7[C]
2004	Gurer-Orhan et al.(105)	Turkey	20	54.6
2004	Chuang et al.(106)	Taiwan	544	23.2
2004	Bagc et al.(107)	Turkey	22	36.8
2004	Heo et al.(25)	South Korea	1123	22.9[D]
2005	Duydu et al.(108)	Turkey	50	40.1
2005	Chuang et al.(109)	Taiwan	855	30.4
2005	Ravichandran et al.(31)	India	171	32.3[D]
2005	Karakaya et al.(110)	Turkey	23	72.7
2006	Patil et al.(111)	India	28	53.6

(Continued on next page)

TABLE II. Arithmetic Mean BLLs of Workers in Lead Battery Manufacturing Plants (*Continued*)

Year	Author	Country	n	Arithmetic Mean BLL (μg/dL)
2006	Kuruvilla et al.(112)	India	52	42.4
2006	Li et al.(113)	Taiwan	597	27.1
2006	Engin et al.(114)	Turkey	30	63.5
2006	Chen et al.(115)	China	25	32.0
2006	Wananukul et al.(24)	Thailand	389	$35.5^{A,D}$
2007	Lin and J. Tai-y (116)	China	135	42.2
2007	Chia(117)	Vietnam	276	25.3^{C}
2008	Chuang et al.(118)	Taiwan	120	37.5^{E}
2008	Raviraja et al.(59)	India	5	81.1^{A}
2009	Kašuba et al.(119)	Croatia	15	43.6
2009	Hsu et al.(120)	Taiwan	80	40.2
2010	Nsheiwat et al.(121)	Jordan	22	27.5
2010	Gao et al.(122)	China	135	42.5^{F}
			Total = 8350	Mean = 47 Median = 42

Note: n = number of samples.

[A] μg/dL conversion from μmol/L.

[B] The number-weighted average of male and female workers reported.

[C] Arithmetic mean computed based on the reported GM and GSD.

[D] Aggregate average provided by authors of the study.

[E] The number-weighted average of Taiwanese and Thai nationals reported.

[F] The number-weighted average of ALAD11 and ALAD12 genotypes reported.

CDC/NIOSH Adult Blood Epidemiology and Surveillance (ABLES) Program project officer, February 2, 2011).(46,47) In an Environmental Assessment filed in 2010, the average BLLs for employees at two lead battery plants at Bristol, Tennessee, and Columbus, Georgia, were reported as 13 and 15 μg/dL, respectively.(41) Since 1993, occupational lead exposures in battery manufacturing declined substantially in the United States due to improvements in ventilation and work practices; environmental lead emission also decreased.(48)

In the U.K., summary data from 2003/2004 indicated that of 11,011 male lead workers undergoing medical surveillance, about 5% had BLLs ≥ 50 μg/dL, and less than 1% had BLLs

TABLE III. Median BLLs of Workers in Lead Battery Manufacturing Plants

Year	Author	Country	n	Median BLL (μg/dL)
1994	Dos Santos et al.(123)	Brazil	166	36.8
1996	Chia etal.(124)	Singapore	72	39.2
1997	Chia(125)	Singapore	50	37.1
1997	Sithisarankul et al.(126)	South Korea	65	27.9
1997	Chia et al.(127)	Singapore	28	42.6
1998	Bergdahl et al.(128)	Russia	42	27.0
1998	Jakubowski et al.(129)	Poland	460	34.9^{A}
1998	Jakubowski et al.(129)	Poland	8	48.2^{A}
1998	Jakubowski et al.(129)	Poland	26	44.9^{A}
1998	Jakubowski et al.(129)	Poland	70	49.6^{A}
1998	Jakubowski et al.(129)	Poland	10	50.3^{A}
2008	Sun et al.(130)	China	155	$20.2^{A,B}$
2008	Sun et al.(130)	China	37	$15.5^{A,C}$
			Total = 1189	Median = 37

[A] Geometric mean considered to approximate the median value.

[B] Male.

[C] Female.

TABLE IV. Arithmetic Mean Blood Lead Levels of Workers in Lead Battery Recycling and Reconditioning Plants

Year	Author	Country	n	BLL (μg/dL)
1995	Yeh et al.(131)	South Korea	31	63.0
1998	Wang et al.(132)	Taiwan	64	66.5
1998	Corzo and Naveda (133)	Venezuela	11	45.8
2000	Mehdi et al.(134)	Iraq	37	60.6
2000	Suplido et al.(135)	Philippines	40	54.2
2001	Cardenas-Bustamante et al.(136)	Colombia	94	88.0
2002	Kumar et al.(137)	India	36	55.6
2002	Ayatollahi(138)	Iran	21	46.8
2008	Minozzo et al.(139)	Brazil	53	59.4
2008	Jiang et al.(140)	China	7	63.5
2008	Ramirez(28)	Peru	41	37.7[A]
2009	Peter(141)	Nigeria-Lagos	20	112.5[B]
2009	Peter(141)	Nigeria-Ibadan	20	93.9[B]
2010	Nsheiwat et al.(121)	Israel	4	43.4
			Total = 479	Mean = 64
				Median = 60

[A] Aggregate average provided by authors of the study.
[B] Two values are from different factories.

TABLE V. Workplace Airborne Lead Concentrations (Arithmetic and Geometric Mean) in Lead Battery Manufacturing and Recycling Plants

Year	Author	Country	Sample Duration, n	Arithmetic Mean Airborne Lead (μg/m^3)	Geometric Mean Airborne Lead (μg/m^3)
1993	Far et al.(71)	Singapore	6 hr, n = 25	NA	98[A]
1994	Ibiebele(52)	Barbados	8 hr, n = 80	NA	33.1[B]
1997	Lai et al.(79)	Taiwan	NR, 219	190	NA
1998	Vaglenov et al.(85)	Bulgaria	7 hr, n = 22	447	NA
1998	Ho et al.(83)	Singapore	6 hr, n = 50	88.6[A]	NA
1998	Ehrlich et al.(84)	South Africa	NR, n = 30	NA	145[C]
2000	Hwang et al.(142)	Taiwan	7 hr, n = 81	NA	107[A]
2002	Wang et al.(53)	China	8 hr, n = 229	206[A]	NA
2002	Hwang et al.(97)	Taiwan	4 hr, n = 96	NA	27.7
2004	Donguk and Namwon(143)	South Korea	8 hr, n = 44	NA	354.8[A]
2005	Ravichandran et al.(31)	India	8 hr, n = 22	384	NA
2006	Chen et al.(115)	China	NR, n = 24	1260	NA
2007	Dyosi(50)	South Africa	8 hr (NR)	321[D,E]	NA
2008	Sun et al.(130)	China	NR	39	NA
		Mean		367	NA
		Median		264	103

Note: NA = not applicable, NR = not reported.
[A] Personal air samples worn on workers.
[B] Combined average values for wet (31.9 μg/m^3) and dry season (34.2 μg/m^3).
[C] Median value.
[D] Combined average values for 2001 and 2002.
[E] Lead battery recycling plant.

TABLE VI. BLLs Reported in Children Residing in Proximity to Lead Battery Manufacturing and Recycling Facilities

Year	Author	Country	n	Age	Distance	Mean BLL (μg/dL)	Median BLL (μg/dL)
1998	Morales Bonilla et al.(144)	Nicaragua	97	6 mo–13 years	200 m	17.2	NA
1998	Tabaku et al.(147)	Albania	84	2–5 years	< 2 km	43.4	NA
1998	Tabaku et al.(147)	Albania	145	2–15 years	<2 km	23.5	NA
1999	Kaul and Mukerjee (145)	Dominican Republic	116	6 mo–10 years	180 m	71.0	NA
1999	Saraci and K. Ziegler-Skylakakis(146)	Albania	194	10–15 years	Not reported	19.3	NA
2000	Suplido and Ong(135)	Philippines	10	6 mo–12 years	20 m	49.9	NA
2003	Cortes-Maramba et al.(148)	Philippines	40	10 years^A	1–5 km	12.9	NA
2006	Safi et al.(149)	Palestinian Authority (Gaza)	435	2–6 years	Not reported	8.6	NA
2007	De Freitas et al.(150)	Brazil	850	6 years^A	<1 km	NA	7.3
2009	Ahmed et al.(151)	Pakistan	190	1–12 years	1 km	12.0	
2010	Khan et al.(57)	Pakistan	123	1–6 years	Not specified	NA	8.1
			Total = 2284			Mean = 29 Median = 19	NA Median = 8

^{A}Average age reported.

$\geq$ 60 μg/dL.(43) Earlier U.K. summary data from 2000–2001 showed that among 3384 male lead battery workers, 11.5% had BLLs $\geq$ 50 μg/dL, and 2.1% had BLLs $\geq$ 60 μg/dL.(42)

Inhalation is considered the most important lead intake route, in general, in occupational settings.(49–51) Ingestion is also a significant source of exposure due to poor hygiene and eating and smoking at the workplace, and from swallowed particles that are trapped in sputum.(49) Studies have documented a strong correlation between airborne lead concentrations with BLL in workers in lead battery factories.(52,53) Consistent with the BLL data reported in Tables II–IV, Table V indicates that airborne lead exposures in lead battery plants in developing countries average more than 7-fold the 50 μg/m^3 permissible exposure limit (PEL) as an 8-hr time-weighted average (TWA) established by the U.S. Occupational Safety and Health Administration (OSHA). In addition, the airborne concentrations reported in developing counties in Table V are substantially higher than those reported among lead battery plants in the United States and Italy (range of 21–45 μg/m^3).(54,55) In addition, among the 250 air samples collected by U.S. OSHA in this industry from 2003–2008, the mean and median airborne concentrations were 57 μg/m^3 and 28 μg/m^3, respectively.(54)

The 10 studies summarized in Table VI suggest that children in communities surrounding lead battery manufacturing and recycling in developing countries had elevated BLLs compared with U.S. children. The average BLL of 29 μg/dL in Table VI is approximately 3-fold higher than the current level of concern for children (10 μg/dL) as established by the CDC. In addition, the geometric mean level in Table VI is approximately 13-fold that reported among U.S. children in the most recent National Health and Nutrition Survey (NHANES) data from 2005–2008.(56) Less dramatic evidence of this pattern was presented in a study conducted in Pakistan that reported a statistically significant higher average BLL in children living closer to lead battery recycling plants compared with controls of similar age living 30 km away (8.1 versus 6.7 μg/dL).(57) It is possible that some of the observed BLLs in these studies were a result of selecting children of employees in these industries with significant contributions due to take-home exposures.

A comparison of the data in Tables II–IV suggests that lead exposures among workers in recycling and reconditioning facilities are higher than those in battery manufacturing operations. In addition, the former operations may also have a greater impact on environmental exposures. Based on the authors' observations, few environmentally sound recycling plants have been built in developing countries, in part because there are no large-scale collection programs to ensure an adequate battery supply to justify the initial capital investment.

In many areas, battery recycling work is done outdoors. Airborne lead emissions settle on soil and result in widespread environmental contamination.(58) In addition, the authors observed that many "backyard" recyclers are located in urban areas with high population densities. Wastewater from battery industries and the acid dumped from recycling operations are major sources of lead contamination in the environment. Many urban residents consume untreated water polluted with lead from these industries, which contributes to the overall population exposure.(57,59)

In considering our finding that the workers in lead battery manufacturing and recycling plants in developing countries have substantially higher BLLs than those in the United States, it is important to consider alternative explanations. First, it is possible the literature was subject to a selection bias in that studies reporting low BLLs were not published because those results were less interesting than studies reporting high BLLs. It is not possible for us to assess the extent of such a publication bias. On the other hand, it is equally plausible that the smallest battery manufacturing/recycling facilities were not surveyed because of the difficulty gaining entry and limitations in sample size, and that these smaller operations had the highest lead exposure levels. This circumstance would impart a bias toward the null in the BLLs reported in the literature.

Second, we excluded four studies from battery manufacturing plants because of incomplete data. A study by Nusier et al.(29) in 2003 reported BLLs by "direct" and "indirect" exposure group in a battery manufacturing facility, but the distinction between these exposure groups was not clear; mean BLL values were 51.4 and 23.9 μg/dL, respectively. Two studies that examined differences in BLLs by genotype did not provide summary measures of exposure.(30) A study by Bhagwat et al.(27) in 2008 provided a combined BLL of 53.6 μg/dL for both battery manufacturing and recycling workers. Because the BLL values in these excluded studies were within the range of reported values in this review, it is unlikely that excluding these studies had much effect on our analysis.

Third, bias may arise due to BLL collection and measurement errors. Samples may be contaminated, as they are generally collected at battery plants. Because BLL tests were conducted in different laboratories in countries without laboratory accreditation or standard reference materials, there is a likelihood of some analytical bias as well as considerable inter- and intra-laboratory variability.(60) However, we are not able to assess the direction and magnitude of this bias. In the future, measurement error can be minimized by introducing standard reference materials and inter-laboratory blood lead proficiency testing programs in these countries.(60)

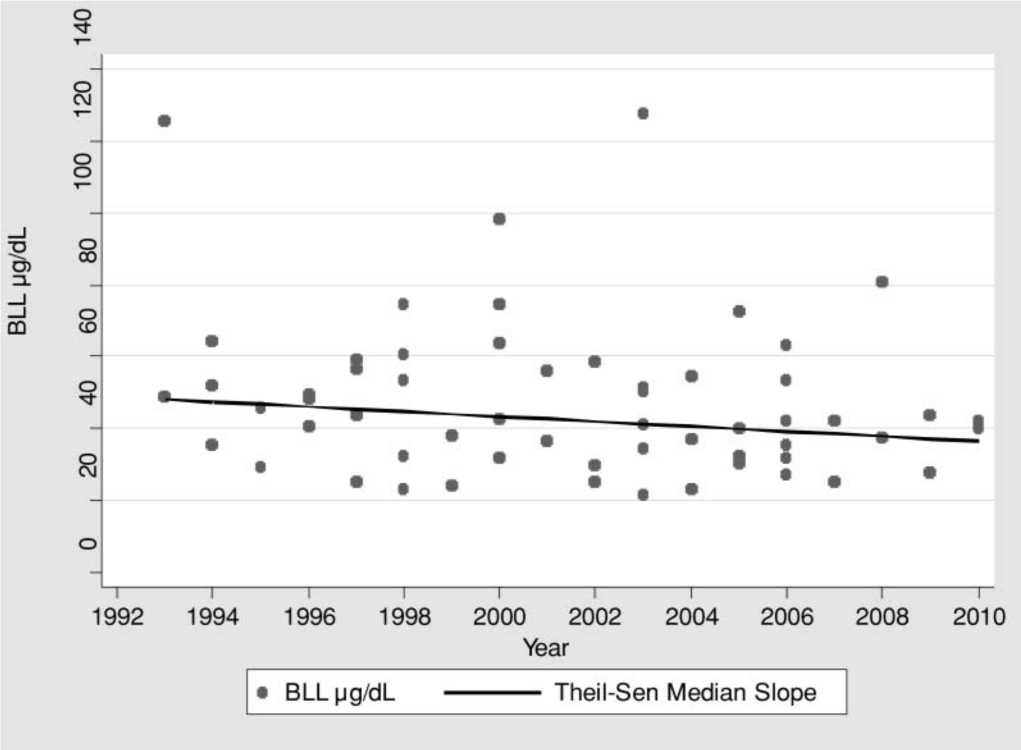

FIGURE 1. The Theil-Sen median trend line for arithmetic mean BLLs among battery manufacturing workers for the years 1993 to 2010. The circles correspond to the 61 individual cohort mean BLLs listed in Table II.

An important limitation of our review is that the majority of studies measured a single blood lead level per subject. The BLL is influenced by recent exposure over several weeks as well as long-term exposures through efflux of lead from bone stores.(61,62) Two or more BLLs measured at different times for each study subject would better reflect the subject's average lead exposure level. On the other hand, in occupational settings with a stable work force and chronic lead exposure, repeated blood lead measurements are likely not highly variable due to the ongoing release of lead into the blood from bone stores.

Similarly, the studies reporting BLLs among children residing near lead battery manufacturing may reflect an episode of acute exposure. Cumulative lead exposures measured in bone would provide the most accurate assessment of lead burden. Unfortunately, there are very few studies with repeated measurements of blood or bone lead in such settings.(63,64) We note that during the time period covered by our review, leaded gasoline was banned or phased out in most countries, with the exception of a small number of African and some Middle Eastern countries.(65,66) Lead exposures from gasoline became less significant over this time, and background BLLs declined.

CONCLUSION

The evidence reviewed from studies published on lead battery manufacturing and recycling in developing countries indicates that exposures are considerably higher than in comparable facilities in the United States and the U.K. Average BLLs reported in developing countries were 47 μg/dL in battery manufacturing plants and 64 μg/dL in recycling facilities. Airborne lead concentrations reported in lead battery manufacturing and recycling in developing countries were approximately 7-fold greater than those observed in the United States. Children living in proximity to lead battery manufacturing and recycling plants in developing countries had exposures that ranged from 4 to 40 times the geometric mean BLLs for children in the United States. Trend analysis for BLLs in the lead battery manufacturing industry over the time period covered by this review suggests that improvements were being made, but such gains were not statistically significant.

The manufacture and recycling of lead batteries can result in lead exposures sufficient to cause chronic and acute health effects. These lead exposures are not evenly distributed across different societies because substantially higher BLLs have been documented in developing countries than in the United States for the past two decades. At the same time, the lower BLLs among U.S. workers show that high lead exposures in this industry are avoidable without the need to develop any new battery processing, ventilation, or furnace technologies. Unless resources are devoted to reduce lead exposures in battery production and recycling, these activities will lead to increased occupational and environmental lead exposure in the developing world.

The battery industry is the largest consumer of lead and will become a larger consumer as the worldwide demand for automobiles increases and substitutes for lead in other products (e.g., paints) are found. The demand for lead is expected to increase disproportionately in developing countries, including China and India, because of several factors. First, environmentally preferable technologies including solar and wind energy are currently reliant on lead batteries for backup power. In China, 75% of all solar installations are linked to lead batteries.(67) Second, lead batteries are used in nearly every cell phone tower to provide backup power. Third, as computers are introduced into rural areas to narrow the "digital divide," more lead batteries will be used for backup power.(68) Consolidation and automation may help reduce the number of workers exposed, but given the fragmented nature of the industry in most developing countries, progress in this respect may be slow.

Fourth, poor manufacturing quality and tropical climates in many developing countries result in a shorter average life of lead batteries and more frequent recycling. Used batteries are broken apart and the metal plates are removed and melted down, often in small fires on the side of a road or in crude smelters, to sell for scrap metal. Because of the poor quality of the material produced by these rudimentary recycling processes, the lead must be melted a second time to remove impurities before it can be used to manufacture new lead batteries.

Many developing countries lack regulations and/or the enforcement capacity to adequately reduce occupational and environmental lead exposures. Alternative means to encourage improvements in the industry should be implemented, including certification programs based on specific occupational, environmental and product stewardship standards verified with independent third-party audits. For example, the Better Environmental Sustainability Targets (BEST) Certification Standard is a comprehensive certification standard developed with involvement of key stakeholders, including industry representatives. The BEST Standard outlines performance measures for workplace exposures, emissions, and extended producer responsibility to take back used batteries for proper recycling.(69) Companies that meet this standard are eligible to become certified and are permitted to place an eco-label on their products to gain recognition for their efforts. Environmental certifications provide opportunities for companies to expand the market for their products, increase prices, and gain competitive advantage.

ACKNOWLEDGMENTS

This research was supported in part by a generous grant from the Richard and Rhoda Goldman Fund. We would like to thank Shannon Selerowski, Carlos Cabrera, Walter A. Alarcon, and Michael Bates for their assistance.

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