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Long-term time trend of lead exposure in young German adults – Evaluation of more than 35 Years of data of the German Environmental Specimen Bank

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A R T I C L E I N F O

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A B S T R A C T

Lead is a ubiquitous pollutant with well-known effects on human health. As there is no lower toxicological threshold for lead in blood and since data gaps on lead exposure still exist in many European countries, HBM data on lead is of high importance. To address this, the European Human Biomonitoring Initiative HBM4EU classified lead as a priority substance. The German Environmental Specimen Bank (German ESB) has monitored lead exposure since more than 35 years. Using data from the early 1980s to 2019 we reveal and discuss long-term trends in blood lead levels (BLLs) and current internal exposure of young adults in Germany. BLLs in young adults decreased substantially in the investigated period. As results from the ESB sampling site Muenster demonstrate, the geometric mean of BLLs of young adults decreased from 1981 (78,7 μg/L) to 2019 (10.4 μg/L) by about 87%. Trends in human exposure closely correlate with air lead levels (ALLs) provided by the European Monitoring and Evaluation Programme (EMEP). Hence, the decrease of BLLs largely reflects the drop in air lead pollution. Known associations of sex, smoking, alcohol consumption, and housing situation with BLLs are confirmed with data of the German ESB. Although internal lead exposure in Germany decreased substantially, the situation might be different in other European countries. Since 2010, BLLs of young adults in Germany levelled out at approximately 10 μg/L. The toxicity of lead even at low levels is known to cause adverse health effects especially in children following exposure of the child or the mother during pregnancy. To identify current exposure sources and to minimize future lead exposure, continuous monitoring of lead intake and exposure levels is needed.

1. Introduction

Lead is omnipresent in our environment and largely emitted from anthropogenic sources. The extensive use and emission of lead and lead-containing compounds resulted in considerable exposure of the environment and the human population in the past (Demirbas et al., 2015; Hernberg, 2000; Nadim et al., 2001; Wu and Boyle, 1997). Currently, the production of lead-acid batteries makes up for the majority of global lead consumption (Davidson et al., 2016; Lopez N et al., 2015). Further sources of human lead exposure include drinking water and several foods, e.g. vegetables and cereals (Brizio et al., 2016; European Food Safety Authority, 2010; Mena et al., 1996; Norton et al., 2015; Pirsaheb et al., 2016; Slepecka et al., 2017; Talio et al., 2014; Zietz et al., 2010). The World Health Organizations (WHO) International Agency for Research on Cancer (IARC) classified lead as possibly carcinogenic to humans (IARC, 1987, 2006). In 2006, the Commission for the Investigation of Health Hazards of Chemical Compounds in the work area of the German Research Foundation (DFG) categorized lead and its inorganic compounds as substances that are considered to be carcinogenic for man (DFG, 2006). In 2009, the German Human Biomonitoring Commission (HBM Commission) discontinued the Human Biomonitoring assessment values (HBM-I- and HBM–II–values) because of the lack of a threshold level for lead toxicity (Apel et al., 2017; Kommission Human-Biomonitoring des Umweltbundesamtes, 2002, 2009). Additionally, in 2010 the Panel on Contaminants in the Food Chain (CONTAM Panel) of the European Food Safety Authority (EFSA) concluded

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that use of the provisional tolerable weekly intake (PTWI) set by the Joint FAO/WHO Expert Committee on Food Additives (JECFA) was no longer appropriate. This conclusion was drawn since no threshold level for toxicological endpoints including developmental neurotoxicity and nephrotoxicity in adults was evident (European Food Safety Authority, 2010; Jeong et al., 2015; Kommission Human-Biomonitoring des Umweltbundesamtes, 2002; 2009; Lanphear et al., 2016; Pawlas et al., 2012). Recent investigations demonstrate that even relatively low blood lead levels (BLL < 50 μg/L) are associated with a reduced cognitive function, e.g. reduced ability to concentrate, and lower IQ in children (European Food Safety Authority, 2010; Jeong et al., 2015; Lanphear et al., 2016; Pawlas et al., 2012). Therefore, serious public health effects are still discussed, especially in children, following exposure of the child or the mother during pregnancy (Clark et al., 2014; Etchevers et al., 2014; Kennedy et al., 2016; Lanphear et al., 2016; Neugebauer et al., 2015). Current examples, e.g. the drinking water contamination of the city of Flint (Michigan, USA) further increase this public concern (Gomez et al., 2018; Pieper et al., 2018). Many countries implemented regulatory actions to reduce human exposure to lead and lead levels in the environment within the last four decades. However, considering Europe, data on lead exposure covering the past five years are only available from seven countries (Rudnai, 2019) and comparable data on exposure levels and trends in exposure are lacking. The European Human Biomonitoring Initiative (HBM4EU, www.hbm4eu.eu) was launched to harmonize Human Biomonitoring efforts in Europe to close data gaps on human exposure in Europe and to provide sound scientific data as a basis for policy decisions, inter alia for lead as a priority substance. Complementary to the representative German Environmental Survey (GerES) the German Environmental Specimen Bank (German ESB) has been monitoring lead exposure in human and environmental samples since the early 1980s. The German ESB is a key element of environmental and human monitoring in Germany and provides valuable policy relevant scientific data on lead exposure in young adults in Germany. In this study, based on the complete dataset of the German ESBs lead monitoring from 1981 to 2019, we show and evaluate the time trend of exposure and evaluate specific factors involved in lead exposure in Germany, to provide an additional building block for evaluating lead exposure in Europe.

2. Material and methods

2.1. The German Environmental Specimen Bank

The German ESBs main goal is to evaluate time trends in pollutant levels in humans and the environment following real time and retrospective monitoring approaches (Kayser et al., 1982; Kemper and Luepke, 1986; Kemper, 1993; Kolossa-Gehring et al., 2012a; Stoeppler et al., 1984; Umweltbundesamt, 1996). Since its foundation in the early 1980s human and environmental samples are stored in a biobank for the unique opportunity of retrospective time trend analysis (Koch et al., 2017; Lermen et al., 2014; Schröter-Kermani et al., 2016; Wiesmüller et al., 2007; Wittassek et al., 2007). Recruitment and sampling have been carried out according to the respective guidelines and standard operating procedures (SOPs) of the German ESB (Eckard et al., 2011; Lermen et al., 2015; Umweltbundesamt, 1996). Briefly, the concept of the German ESB stipulates an annual cross-sectional sampling of approximately 120 volunteering students on each of the four different sampling sites Muenster, Ulm (both former Western Germany), Halle (Saale), and Greifswald (both former Eastern Germany). In total approximately 480 participants have been recruited annually. Participation is limited to healthy adults aged 20–29 in a balanced sex ratio. Each year young adults, have been recruited by promoting the study at the medical faculties of the universities at the four sampling sites by sending out e-mails to all students of the respective medical faculties, promoting the study before lectures, and by distributing flyers at the respective medical faculty. As only young adults were recruited out of medical students, it can be assumed that the sample is mainly composed of individuals that are not occupationally exposed. Thus, results can be assumed to represent the background exposure in Germany (Umweltbundesamt, 2008). The German ESB focuses on the investigation on long-term trends in exposure and supplements the German Environment Surveys (GerES), Germany's representative large-scale population study on exposure to environmental pollutants being conducted in a five-year cycle (Kolossa-Gehring et al., 2012b). Blood samples were taken under medical supervision. For retrospective analyses, aliquots of the collected samples have been stored at ultra-low temperatures in the German ESB. Samples collected after 2010 are stored in the gas phase of liquid nitrogen (LIN) at temperatures below −130 °C. In 2013, all samples collected before 2010 were transferred from −80 °C freezers into LIN-based storage systems and have since then also been stored at temperatures below −130 °C (Lermen et al., 2014). The concept of the German ESB and the SOPs are available online (https://www.umweltprobenbank.de/en/documents/publications). The current study protocol for the sampling of human samples from young adults was reviewed and approved in 2011 by the ethics committee of the Medical Association Saarland, Germany. Before 2011, the study protocol was reviewed and approved by the ethics committee of the Medical Association Westphalia-Lippe and the Medical Faculty of the University of Muenster, Germany. All study participants gave written informed consent on standardized forms approved by the ethics committees. The right to know and the right not to know were guaranteed. The results were reported to the participants immediately after the analyses were completed.

2.2. Questionnaire data

To document the medical history, exposure-relevant behavior (e.g. nutrition, smoking, and drinking habits), and living conditions, a self-administered questionnaire has been used. Limitations in recording exposure-relevant aspects exist for some influencing factors. For example, since many of the German ESB participants are students who mostly live in rented and/or shared flats, information on the material and condition of water pipes is only partly known to participants and therefore not investigated in this study. From 1981 to 2019, questions regarding smoking status were adapted multiple times and consequently evaluation for the whole time period was only possible on a yes or no basis. Since 2007, smoking status was consistently recorded using the following categories: non-smoker (NS), non-smoker but second-hand smoker (NS but SHS), ex-smoker but second-hand smoker (ES but SHS), smoker (S). Questions regarding the consumption of alcoholic beverages were also slightly adapted during the time period inspected. Alcohol consumption was expressed in a binary fashion (yes or no) for analyses.

2.3. Blood lead level determinations

After completing all sampling processes of one year at the four sampling sites, the entire batch of samples was analysed to be able to report continuously. In order to be able to distinguish potential geographical differences from analytical effects, samples of one year were measured in randomized order. Since data on blood lead values of the German ESB have been recorded over 35 years, variations exist with regard to the applied methods of chemical analysis. Electrothermal atomic absorption spectrometry at 283.3 nm with Zeeman background compensation using graphite furnace technology (ET-AAS-Z) was used from 1981 until 1999. In 1999, inductively coupled plasma mass spectrometry (ICP-MS) was used for the first time to analyse samples of one sampling site (Muenster). In 2000 and 2001, ICP-MS was used for all four sampling sites followed by high-resolution inductively coupled plasma mass spectrometry (HR-ICP-MS) in a multi-element analysis mode from 2002 to 2009. In 2010, the analytical method was changed back to ICP-MS, since a limit of quantification (LoQ) of 0.15 μg/L was considered sufficient providing reliable data for blood lead quantification. However, the previously described changes in analytical methods led to changes of the respective limits of quantification (see Table 1 for details on LoQs). This is especially relevant in the years preceding the introduction of ICP-MS (1996–1999), where average blood lead levels approached the LoQ of the ET-AAS-Z method, leading to a high percentage of measurement values below the LoQ (15%–35%). From 1981 to 1994, measurements under LoQ ranged from 0% to 2% and from 1995 to 1999 from 15 to 35%. From 2000 to 2019, all samples were above LoQ. Lead concentration was determined by isotope analysis of ^{207}Pb in low (ICP-MS) or medium resolution setting (HR-ICP-MS). Before analysis, whole blood samples were wet-digested by microwave heating with high pressure (Teflon) vessel technology using nitric acid and hydrogen peroxide as oxidation agents. Until 2010, blood lead analysis was performed by the University of Muenster. Since 2011, analysis has been conducted by the Institute and Outpatient Clinic of Occupational, Social and Environmental Medicine, Friedrich-Alexander-University Erlangen-Nürnberg, Erlangen (IPASUM). All analytical methods were based on respective guidelines of the German Environmental Specimen Bank (Umweltbundesamt, 1996). Quality assurance was improved over time considering internal and external control schemes. Quality control for lead analysis has been conducted according to external quality assessments schemes (GEQUAS) and the measurement of certified reference material (NIST-CRM) explained in detail elsewhere (Göen et al., 2012). Quality was assured with regularly participation in GEQUAS round robin tests.

2.4. Statistical analyses

The statistical analyses were carried out using R Version 3.2.3. Blood lead values below LoQ were replaced by LoQ/2 (Hornung and Reed, 1990). P values ≤ 0.05 were considered statistically significant. Trends of geometric mean (GM) BLL values from 1981 to 2019 were assessed separately for male and female participants and tested for the presence of monotonic trends (Mann-Kendall test) using the function “mk.test” from the R package “trend” v1.0.1. Presence of an exponentially declining trend was evaluated by fitting a function of the form GM BLL (year) = a * exp(b*year) + c to the geometric mean BLL values using the non-linear least squares method (function “nls” from R package “stats” v3.4.4). Significance of Pearson’s product moment correlation coefficients was assessed using the function “cor.test” from R package “stats” v3.4.4.

To explore further BLL-affecting factors we investigated BLL values of the years 2010–2019. Since BLL values levelled at a plateau following the year 2010, the period from 2010 to 2019 was chosen to minimize confounding differences between locations and sampling years. Due to partly lacking variance homogeneity (Levene test) and deviations from normal distribution (Kolmogorov-Smirnov test), differences between groups were analysed using non-parametric tests. Differences of two groups (e.g. no alcohol consumer vs. alcohol consumer) were analysed with the Mann-Whitney *U* test. For the comparison of smoking categories, a Kruskal-Wallis test, followed by Dunn post hoc tests with Bonferroni correction were used. Housing situation was categorized according to the risk of white lead paint being used as coating. Houses and apartments built before 1949 were assumed to represent a higher risk and were aggregated as “old buildings”. Houses and apartments built since 1949 were considered to represent a lower risk and were aggregated as “new buildings” (Falq et al., 2011; Lucas et al., 2012; Meyer et al., 1999).

Table 1
Overview of LoQ with respect to the different analytical methods used for blood lead analysis over time.

Sampling site	until 1998	1999	2000–2001	2002–2009	since 2010
Muenster	20 μg/L[a]	0.01 μg/L[b]	0.01 μg/L[b]	0.01 μg/L[c]	0.15 μg/L[b]
Halle	20 μg/L[a]	20 μg/L[a]	0.01 μg/L[b]	0.01 μg/L[c]	0.15 μg/L[b]
Greifswald	20 μg/L[a]	20 μg/L[a]	0.01 μg/L[b]	0.01 μg/L[c]	0.15 μg/L[b]
Ulm	20 μg/L[a]	20 μg/L[a]	0.01 μg/L[b]	0.01 μg/L[c]	0.15 μg/L[b]

[a] EZ-AAS-Z.
[b] ICP-MS.
[c] HR-ICP-MS.

3. Results

3.1. Trend of blood lead concentrations

German ESB data from Muenster students cover over 38 years (1981–2019) and include 3851 young adults aged 20–29 years (Fig. 1). Geometric mean (GM) BLLs of female and male participants decreased by about 87-88% from 1981 to 2019 (females: 72.2 to 8.4 μg/L, males: 85.3 to 11.0 μg/L) and followed monotonically decreasing trends ($p < 0.001$, Mann-Kendall test). More specifically, the reduction in GM BLLs was closely approximated by a trend function decreasing exponentially over time (Root mean square deviation (RMSD): 4.6 μg/L (females), 5.4 μg/L (males); adjusted R^2: 0.94 (females), 0.95 (males)). GM BLLs at the other three sampling sites also followed significant monotonically decreasing ($p < 0.005$, Mann-Kendall test) and similarly shaped trends (Fig. 2). Based on data of all four sampling sites combined, GM BLLs decreased by 53.1% from 24.0 μg/L in 1997 to 11.56 μg/L in 2010. A significant decrease of GM values was not observed following the year 2010 ($p = 0.07$, Mann Kendall test). The whole dataset can be accessed on the German ESBs webpage (German ESB, 2020).

In early years (1986–1990 and 1995–1996), in addition to the sample collections during the winter season, an additional sample collection during summer was carried out each year in Muenster. In the additional dataset, systematic seasonal effects on blood lead levels were not detected (c.f. Supplementary Fig. 1).

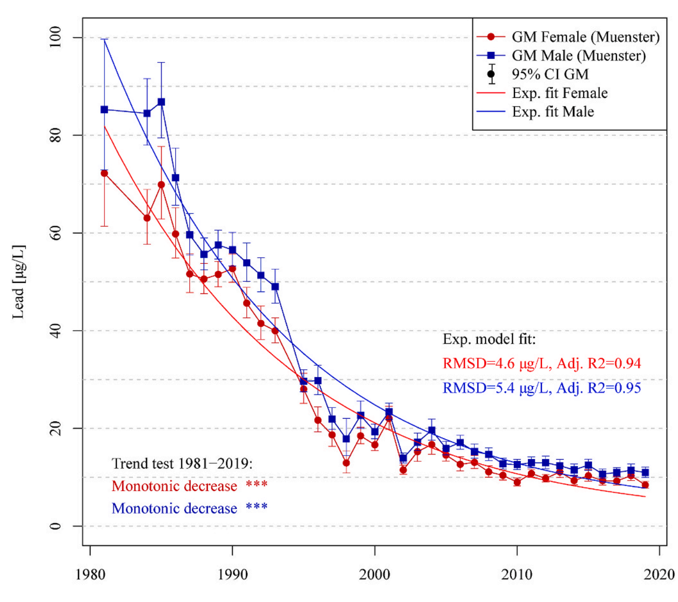

Fig. 1. Blood lead concentration of young adults from the sampling site Muenster from 1981 to 2019. Shown are the yearly geometric mean (GM) values of male and female participants with their 95 percent confidence intervals as well as the model fit of an exponentially decreasing trend function.

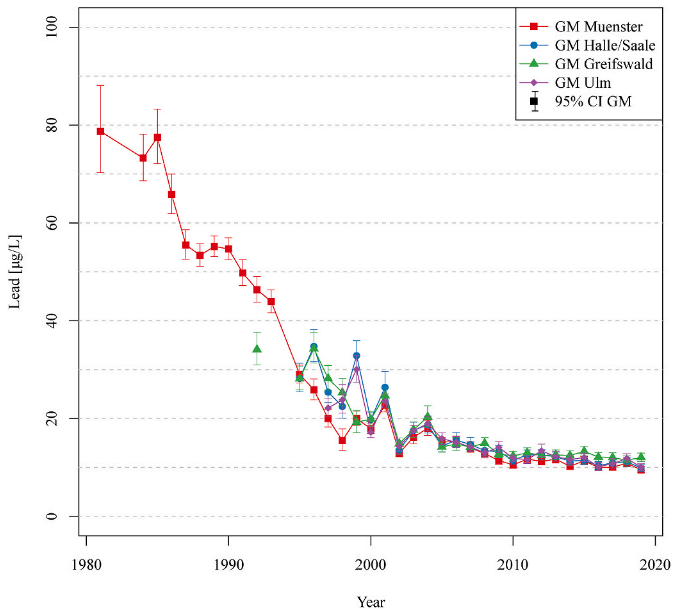

Fig. 2. Geometric mean blood lead concentrations from all four sampling sites of the German ESB. Muenster (1981–2019), Greifswald (1992–2019), Halle (1995–2019), and Ulm (1997–2019). 95 percent confidence intervals of GM values are depicted as error bars.

3.2. Further factors associated with blood lead levels: sex, housing, smoking status, and alcohol consumption

To explore further BLL-affecting factors we investigated the years 2010–2019. An overview of BLLs from young adults grouped according to selected factors and considering data of all four sampling sites from 2010 to 2019 is given in Table 2. In general, male participants had significantly higher median BLLs than females (12.4 µg/L versus 10.2 µg/L). Approximately one quarter of participants (males: 24.5%, females: 23.9%) from samplings in 2010–2019 lived in houses build before 1949 and this percentage did not change substantially during the time period investigated. Statistically significant differences between non-smoking participants living in old and new buildings were only found in males (12.9 µg/L (old building) versus 12.0 µg/L (new building); females: 10.1 µg/L versus 9.9 µg/L). Both female and male smokers showed significantly higher BLLs than respective non-smokers (females: 13.3 µg/L versus 9.9 µg/L; males: 14.4 µg/L versus 12.1 µg/L). Although the prevalence of smokers decreased during the investigated period from 2010 to 2019 (females: 15.0%–4.2%, average 10.1%; males: 22.8%–12.8%, average 15.7%), the relative increase in BLLs of smokers versus non-smokers in individual years was comparable to the dataset as a whole.

To evaluate the impact of second-hand-smoke on the BLL we divided the group of non-smoking individuals into the groups of non-smokers (NS), non-smokers but second-hand-smokers (NS but SHS), ex-smokers (ES) and ex-smokers but second-hand-smokers (ES but SHS) and compared their data to the BLLs of smokers (S) (Fig. 3). S had significantly higher BLLs than all other groups in both sexes. An effect of second-hand-smoking was only detectable in females, with NS but SHS having significantly higher BLLs than NS. ES showed elevated BLLs in comparison to NS in both sexes. In the female group, ES and NS but SHS showed similar BLLs at an intermediate level between BLLs of NS and S. In the male group, ES showed BLLs closer to the level of current smokers. The relatively small group size of ES but SHS (males: n = 75; females n = 57) hampered detection of statistically significant differences to other groups. In terms of BLLs however, ES and ES but SHS showed very similar geometric mean values in both sexes. Prevalence of alcohol consumers among participants was high (males: 93.9%; females: 91.9%) and did not change substantially over the time period investigated. Among non-smokers, median BLLs of female and male alcohol consumers were significantly higher compared to female and male participants who did not self-report alcohol consumption (females: 10.1 µg/L vs 8.8 µg/L; males: 12.2 µg/L vs 11.1 µg/L).

4. Discussion

4.1. Trend of Pb exposure and international comparison

The German ESB has been monitoring lead exposure of young adults since 1981. Data from 1981 to 2019 show a substantial decrease in lead exposure in young adults in Germany (approx. 87%). A detailed history of European gasoline lead content regulations and especially their implementation in Germany is given in (von Storch et al., 2003). Lead emission decreased in Germany continuously from the mid-80s due to different iterative mitigation steps. Data on regional air lead levels (ALLs) at the four German ESB sampling sites, compiled by the European Monitoring and Evaluation Programme (EMEP) for the same period show trends that corresponded to the observed change in German ESB BLLs remarkably well (see Supplementary Fig. 2). A similar correlation between ALLs and BLLs and a comparable decrease of both after the

Table 2
Blood lead concentrations: medians, arithmetic means (±SD), geometric means (95% CI), 95th percentiles, ranges in German young adults aged 20–29 by sex.

2010–2019		n	MD	AM (±SD)	GM (95% CI)	95th PE	Min	Max	MW-Test[1]
Female	Total	2626	10.2	11.6 (±6.2)	10.5 (10.3–10.7)	21.8	2.8	103.1	p < 0.001
Male	Total	2310	12.4	13.9 (±7.0)	12.7 (12.4–13.0)	26.1	3.0	98.5	
Female participants									
Non-smoker		2345	9.9	11.3 (±5.8)	10.3 (10–10.5)	21.2	2.8	71.9	p < 0.001
Smoker		265	13.3	14.5 (±8.3)	13.1 (12.1–14.1)	24.7	4.2	103.1	
Female non-smokers									
No alcohol consumer		205	8.8	11.1 (±8.0)	9.6 (8.5–10.7)	25.6	2.9	71.9	p < 0.001
Alcohol consumer		2140	10.1	11.3 (±5.5)	10.3 (10.1–10.6)	21.1	2.8	66.9	
Living in new building[2]		1648	9.9	11.3 (±5.7)	10.2 (10.0–10.5)	21.1	2.8	71.9	p = 0.363
Living in old building[3]		539	10.1	11.6 (±6.2)	10.5 (10.0–11)	21.9	3.9	66.9	
Male participants									
Non-smoker		1930	12.1	13.5 (±6.9)	12.3 (12–12.6)	24.4	3.0	98.5	p < 0.001
Smoker		363	14.4	16.4 (±7.4)	15 (14.3–15.8)	30.4	5.6	55.4	
Male non-smokers									
No alcohol consumer		132	11.1	12.5 (±8.0)	10.9 (9.5–12.3)	23.3	3.5	61.9	p = 0.002
Alcohol consumer		1798	12.2	13.5 (±6.8)	12.4 (12.1–12.7)	24.5	3.0	98.5	
Living in new building[2]		1387	12.0	13.2 (±6.7)	12.1 (11.7–12.4)	22.8	3.0	98.5	p = 0.002
Living in old building[3]		444	12.9	14.4 (±7.6)	13 (12.3–13.7)	27.5	3.9	77.7	
Total		4936	11.2	12.7 (±6.7)	11.5 (11.3–11.7)	23.6	2.8	103.1	

Lead concentrations is given in µg/L, [1]Mann-Whitney test, [2]built since 1949, [3]built before 1949.

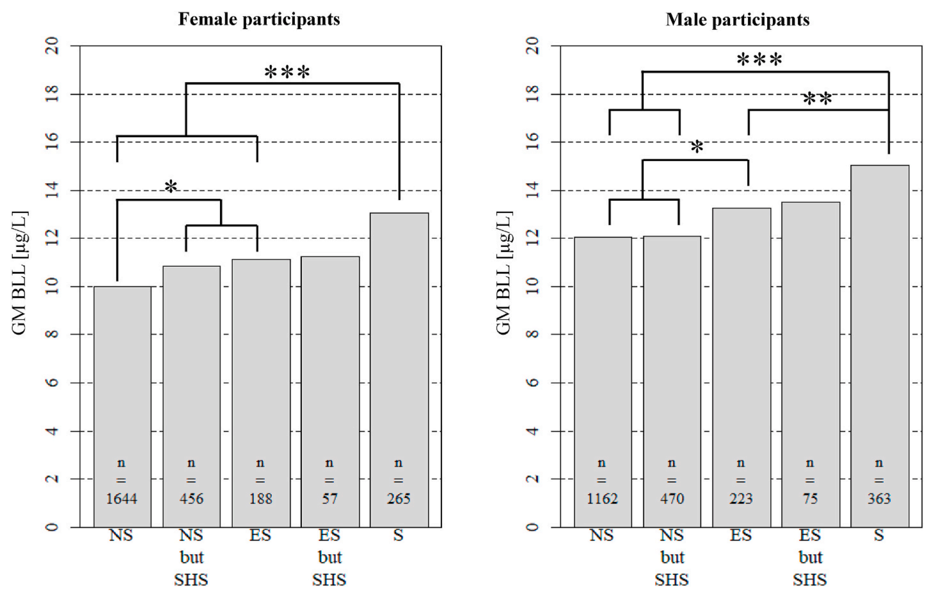

Fig. 3. Geometric means of BLLs [µg/L] of male (a) and female (b) non-smokers (NS), non-smokers but second-hand smokers (NS but SHS), ex-smokers (ES), ex-smokers but second-hand smokers (ES but SHS) and smokers (S) at all sampling sites from 2010 to 2019. Statistical significance of differences: *p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001.

implementation of political mitigation measures was also found in other European countries (Bono et al., 1995; Petit et al., 2015; Rodamilans et al., 1996), and globally (e.g, USA, Richmond-Bryant et al., 2014, South Korea, Oh et al., 2017). Our findings therefore strongly support that the observed steep decrease of BLLs is to a large degree a reflection of the drop in air lead pollution.

Although the toxicity of lead at low levels is still highlighted due to its adverse health effects on the fetus and children, still data gaps on exposure levels exist on a global scale. In Europe only few Human Biomonitoring studies on lead exposure were conducted in the last decades. However, comparability of results is limited due to different study designs, different target groups, and different points in time (Rudnai, 2019). Comparable data on trends in exposure are highly relevant for the evaluation of exposure in Europe and the implementation of adequate political mitigation measures and the control of its effects. First attempts in harmonizing HBM activities in Europe started already 2005 with the EU project ESBIO (Joas et al., 2012) and was continued subsequently in 2009 with the EU twin project COPHES/DEMOCOPHES (Schindler et al., 2014; Schwedler et al., 2017). Currently the European HBM initiative HBM4EU (www.hbm4eu.eu) is driving harmonization activities to improve collection and assessment of policy relevant data and feed them into open policy processes. Data on a comparable age group (25–35 years) as the German ESB students are provided by the Swedish MONICA study. BLLs in Sweden decreased drastically since the 1990s and show no further significant decrease since 2009 (Wennberg et al., 2017) which is in line with German ESB data. Latest results of the MONICA study reveal median BLLs of Swedish young adults aged 25–35 of 11 µg/L in males and 9.65 µg/L in females in 2014 (Wennberg et al., 2017) which agrees with the BLLs of young adults in Germany at this time.

For the years 2006–2007, the French Nutrition and Health Survey (ENNS) provides a blood lead geometric mean value of 25.7 µg/L (95% CI: 24.9 µg/L – 26.5 µg/L) for the French population aged 18–74 (Falq et al., 2011). For the subgroup of French adults aged 18–39 a GM value of 18.7 µg/L (95% CI: 17.8 µg/L – 19.6 µg/L) is reported. Regarding the years 2009 and 2010, the Spanish BIOAMBIENT study gives a first baseline information with a mean (GM) BLL of 24.0 µg/L (95% CI: 23.0 µg/L – 25.1 µg/L) for Spanish adults aged 18–65 (Cañas et al., 2014). For the age group 18–29, the BIOAMBIENT study reports a GM BLL of 19.1 µg/L (95% CI: 17.9 µg/L – 20.1 µg/L). Although age groups of these two studies are slightly different, compared to the mean values (GM) of 14.7 µg/L in 2006/2007 and of 12.1 µg/L in 2009/2010 for young adults in Germany aged 20–29, French and Spanish adults seem to have slightly higher mean BLLs in the respective years.

Results of the latest Canadian Health Measures Survey (CHMS) are based on data of the years 2016–2017 and report a mean (GM) BLL from adults aged 20–39 of 7.8 µg/L (Health Canada, 2019) while German ESB data indicate a GM BLL value of 11.7 µg/L in 2014/2015.

The US National Health and Nutrition Examination Survey (NHANES) provides data on BLLs of US citizens which are 20 years and older. Nevertheless, regarding the years 2001–2016, BLLs in the US and Germany decreased in a comparable manner (see Table 3). Within 16 years, NHANES data demonstrate that the mean blood lead concentration (GM) of American adults at the age of 20 years and older decreased by 41% from 15.6 µg/L to 9.2 µg/L (Centers for Disease Control and Prevention, 2009, 2014, 2019). During this time period, blood lead values of German ESB participants aged 20-29 decreased by 36.9% from 17.9 µg/L in 2001/2002 to a mean blood lead value (GM) of 11.3 µg/L in 2015/2016.

Data on lead exposure show a reduction in BLLs over time on a global scale and thus confirm the success of multiple mitigation measures implemented on national and international levels like the ban on leaded gasoline. Its impact on lead exposure has been intensively described (Bierkens et al., 2011; Muntner et al., 2005; Smolders et al., 2010; Strömberg et al., 2008; Thomas et al., 1999; von Storch et al., 2003). However, the national differences in concentration levels inevitably raise questions on different methodologies, different exposures and exposure sources and should be subjected to further research.

4.2. *Further factors associated with blood lead levels*

Since 2010 BLLs of young adults in Germany reached a stable plateau. This background exposure might be a complex mix of multiple exposure sources influenced by individual life style and dietary habits as well as social status, as discussed below (Cañas et al., 2014; Grandjean et al., 1981; Richter et al., 2013; Symanski and Hertz-Picciotto, 1995; Vahter et al., 2007; Wennberg et al., 2017; Weyermann and Brenner, 1997).

Amongst lifestyle habits, smoking and alcohol consumption have been discussed to be of highest relevance for human lead exposure

Table 3
Blood lead levels for the U.S. population from the NHANES aged 20 and older and from the German ESB aged 20–29 from 2001 to 2016.

Years	NHANES			German ESB		
	GM (95% CI)	MD (95% CI)	Sample size	GM (95% CI)	MD (95% CI)	Sample size
01-02	15.6 (14.9–16.2)	16.0 (15.0–16.0)	4772	17.9 (17.4–18.5)	17.9 (17.5–18.2)	837
03-04	15.2 (14.5–16.0)	15.0 (14.0–16.0)	4525	18.1 (17.5–18.7)	17.6 (17.3–17.9)	896
05-06	14.1 (13.4–14.8)	14.1 (13.3–14.8)	4509	15.0 (14.6–15.5)	14.9 (14.7–15.2)	856
07-08	13.8 (13.1–14.6)	13.4 (12.6–14.2)	5364	13.9 (13.5–14.3)	13.9 (13.7–14.2)	875
09-10	12.3 (11.9–12.8)	12.0 (11.4–12.5)	5765	12.1 (11.8–12.4)	12.0 (11.8–12.2)	876
11-12	10.9 (10.3–11.6)	10.5 (10.0–11.2)	5030	12.3 (12.0–12.6)	12.1 (11.9–12.3)	968
13-14	9.7 (9.2–10.0)	9.4 (9.0–9.8)	2695	11.7 (11.4–12.1)	11.2 (11.0–11.4)	986
15-16	9.2 (8.6–9.8)	8.8 (8.1–9.6)	2610	11.3 (11.0–11.6)	11.2 (11.0–11.3)	995

Lead concentrations are given in μg Pb/L whole blood, GM = Geometric Mean, MD = Median, CI = confidence interval.

(Grandjean et al., 1981; Grasmick et al., 1985; Richter et al., 2013; Shaper et al., 1982). In the period of relatively low environmental background exposure since 2010, the German ESB data clearly confirm the association of smoking and alcohol consumption on BLLs. As the investigated group consisted of young adults highly unlikely occupationally exposed to lead, smoking and alcohol consumption can be considered as main factors with high impact on current lead exposure next to food and drinking water, which could not be evaluated in this study. German ESB data also revealed that past smoking is still a determinant for the current internal lead exposure (see Fig. 3). Effects of housing on lead exposure in non-smoking participants could only be found in male participants. In general, male participants had higher BLLs than females what is in line with findings from other studies (Cañas et al., 2014; Falq et al., 2011; Health Canada, 2017, 2019; Muntner et al., 2005; Wennberg et al., 2017). In a recent study with a focus on international comparison limited to female participants (including German ESB BLL data), BMI seems to be somewhat associated with BLL which is, however, in disagreement with findings from other studies (Nakayama et al., 2019). Specific studies need to assess the impact of personal behavior on the BLL and need to clarify the sources for the current low-level background exposure in Germany in more detail, to enable further decrease in lead exposure. Specifically, some foods and drinking water are known exposure sources in this context and have to be included in more detailed investigations (Brizio et al., 2016; European Food Safety Authority, 2010).

4.3. Current lead exposure

BLLs in young adults in Germany decreased by more than 85% from 1981 to 2010 (GM: 78.7 to 11.56 μg/L) and since then stabilized on a plateau. Recent studies reported that even a low level of lead exposure is associated with negative impact on human health for adults and children (Canfield et al., 2003; Falck et al., 2019; Grönqvist et al., 2020; Lanphear et al., 2000, 2016, 2018; Zhou et al., 2020). Especially during pregnancy and in young children, blood lead levels below 10 μg/L are found to have detrimental effects (Afeiche et al., 2011; Jakubowski, 2011; Motao Zhu, 2010; Xie et al., 2013). Thus, based on current data no threshold for lead toxicity can be derived. Current BLLs have to be monitored regularly especially in children and women of childbearing age and the ubiquitous exposure has to be further reduced to conciliate public health concerns. Considering potential European regulation measures, the generation of comparable data on lead exposure has to be facilitated and monitoring efforts have to be harmonized to paint a clear picture of lead exposure across borders.

5. Conclusions

Overall, human lead exposure decreased drastically in Germany over the last 38 years. Clearly, regulatory actions on lead emissions compassed a significant positive impact on human lead exposure. But current exposure levels still encompass BLLs considered unsafe and no further decrease could be seen in the last decade. Previous regulatory measurements have apparently reached their level of influence and should therefore be improved. A further reduction of lead exposure in the future is still necessary. An extensive monitoring of both, lead intake (monitoring of food and other sources) and exposure (HBM) to uncover the specific sources relevant for current lead exposure will be needed, especially in more sensitive parts of the population like children and women of childbearing age, to characterize their special risks. International harmonization of the national monitoring efforts, like HBM4EU (Ganzleben et al., 2017), will further improve the knowledge base and therefore support action on a global scale.

Declaration of competing interest

The authors of this manuscript certify that there are no actual or potential competing financial interests and that the authors' freedom to design, conduct, interpret, and publish research is not compromised by any controlling sponsor as a condition of review and publication.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2020.113665.

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