Environment International 37 (2011) 565–571

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Blood lead levels in the adult population living in France the French Nutrition and Health Survey (ENNS 2006–2007)

Grégoire Falq [a,*], Abdelkrim Zeghnoun [a], Mathilde Pascal [a], Michel Vernay [b], Yann Le Strat [c], Robert Garnier [d], Didier Olichon [e], Philippe Bretin [a], Katia Castetbon [b], Nadine Fréry [a]

[a] Institut de Veille Sanitaire, Département Santé Environnement, Saint Maurice, France
[b] Institut de Veille Sanitaire, Unité de Surveillance en Epidémiologie Nutritionnelle/Université Paris 13, Bobigny, France
[c] Institut de Veille Sanitaire, Département des Maladies Infectieuses, Saint Maurice, France
[d] Centre Anti-Poison, Hôpital Fernand-Widal, Paris, France
[e] Laboratoire Pasteur-Cerba, Cergy-Pontoise, France

ARTICLE INFO

Article history:
Received 13 April 2010
Accepted 26 November 2010
Available online 14 January 2011

Keywords:
Human biomonitoring
Blood
Lead
Exposure
Population study

ABSTRACT

Background: The French Nutrition and Health Survey (ENNS) was conducted in order to describe food consumption and levels of various biomarkers in the general population. In this paper, we aimed to assess the distribution of blood lead levels (BLL) in the adult population living in France.

Method: ENNS was a cross-sectional survey carried out in the general population. Participants (18–74 years of age) were sampled using a three-stage probability design stratified by geographical areas and degrees of urbanization. Collected data included biochemical samples, anthropometric measurements, socio-demographic characteristics, and environmental and occupational exposure.

Results: In 2006/2007, 2029 adults were included in the survey on lead. The blood lead geometric mean (GM) in the population living in France was 25.7 μg/L [24.9–26.5]. The overall prevalence of elevated BLL (>100 μg/L) was 1.7% [1.1–2.3%]. Levels were significantly higher in males than in females, and increased with age, smoking status and alcohol consumption. Other factors significantly associated with BLL were leisure activities, occupational category, age of housing unit, birth place and shellfish/crustacean consumption.

Conclusion: For the first time a survey provides national estimates of BLL for the adult population in France. Comparison with results from a previous study among men aged 18–28 years showed that the GM dropped more than 60% in the last 10 years. The distribution of BLL in France was quite similar to that observed in other European countries.

1. Background

Adverse effects caused by lead exposure have been recognised for centuries. Many studies (Staessen et al., 1996; INSERM, 1999; INSERM/InVS, 2008) have described deleterious effects on multiple organ systems including the nervous, hematopoietic, renal, endocrine and reproductive systems.

Lead exposure pathways remain various: contaminated dust ingestion, food and water ingestion and air inhalation (INSERM, 1999). Contamination of drinking water may occur through plumbing containing lead such as solder, pipes, pipe fittings and sediments. Food contamination may occur during the production process or through the contact with the packaging (IPCS, 1995). Moreover some food products may contain high lead concentrations (Glorennec et al., 2007), such as shellfish, fish or offal. Homes may be contaminated by lead dust, when they were built before 1948 (white lead-based paint was still used in France until 1948) especially when damaged or when there was home renovation with dust emission (scraping/sanding activities or painted component removal) (IPCS, 1995). Leisure activities may also expose to lead for example through activities such as shooting, painting or pottery.

Lead concentration in whole blood (BLL) is the main biomarker used to monitor exposure and has been widely used in numerous epidemiological studies (Huel et al., 2002; CDC, 2005; Batariova et al., 2006; Becker et al., 2002). BLL is a balance between recent absorption of lead and a removal of lead stored in the body, especially in bone (Christoffersson et al., 1986; Nilsson et al., 1991) and is representative of the internal dose of lead in the organism when the exposure is stable (Barbosa et al., 2005).

In recent decades in France, intensive actions directed at primary prevention have been taken to further reduce lead exposure from gasoline, paint, solder and other sources. Nonetheless, lead remains present, because of its wide dispersion over many decades and its

Abbreviations: ENNS, Etude National Nutrition Santé (The French Nutrition and Health Survey); BLL, Blood Lead Levels; log-BLL, Natural logarithm of blood lead levels; LOD, Limit of detection; LOQ, Limit of quantification; InVS, Institut de Veille Sanitaire (French Institute for Public Health Surveillance); GM, Geometric mean.

* Corresponding author. Institut de Veille Sanitaire, Département Santé Environnement, 12, rue du val d'Osne 94410 Saint Maurice, France. Tel.: +33 1 41 79 69 61; fax: +33 1 41 79 67 68.
E-mail address: g.falq@invs.sante.fr (G. Falq).

0160-4120/$ – see front matter
doi:10.1016/j.envint.2010.11.012

continuing industrial uses. Previous studies in three urban French cities (Paris, Marseille and Lyon) have shown a strong decrease in BLL (a reduction of 60 μg/L in the arithmetic mean) from 1979 to 1996 (Huel et al., 2002). A study conducted in 1995 (INSERM/RNSP, 1997) gave first estimates at a national level for children and young men. However, in France, few biomonitoring data are available at the national level for pollutants. The main objectives of the French Nutrition and Health Survey (ENNS), carried out by the French Institute for Public Health Surveillance (InVS) in 2006–2007 (Castetbon et al., 2009), were to describe food consumption, nutritional status, and physical activity in the general population in France (adults and children) and to study nutritional and environmental biomarkers. ENNS was designed to estimate levels of various different metals (including lead, cadmium, mercury and arsenic) and pesticides (organophosphates, organochlorines and pyrethroids) in blood, urine and hair.

This paper describes the distribution of blood lead levels in the adult population (18–74 years old) living in France in 2006–2007. We also attempt to evaluate the socio-demographic and environmental exposure factors that are important in explaining the variations of BLL.

2. Methods

ENNS was a cross-sectional study carried out in the general population included over one year between 2006 and 2007, in order to account for seasonal changes in diet. The participants were randomly sampled using a three-stage probability design. In the first stage, primary sampling units (towns or groups of towns) were selected from a sampling frame, stratified by geographical areas (8 regions) and degree of urbanization (4 strata: rural; <20,000 inh.; 20,000–100,000 inh.; >100,000 inh.). In the second stage, households were selected from three different phone user databases (including mobile phones). The number of households selected in each of the 32 strata was determined according to the population belonging to each stratum (French census 1999). Finally, one household member (an adult or a child) was selected in each household, using the next birthday method.

Approval for the study was obtained from the French data protection authority (Commission nationale de l'informatique et des libertés, authorization no. 905,481) and a bioethic committee (Hôpital Cochin, Paris, no. 2,264). Each subject who was sampled was asked to complete informed consent documents and had the possibility to withdraw at any time his/her participation in the study.

Criteria for adult eligibility for the food consumption survey were as follows: residence in continental France during the period of the study, age 18–74 years, normal living accommodation for at least 5 days a week (not in an institution) with phone contact, an understanding of the issues of the study, no artificial feeding, and agreement to participate in the study. Individual and health characteristics, eating habits, and occupational and environmental exposures were collected through interviews and self-questionnaires.

Subjects were included in the lead study when they agreed to participate in the clinical and biochemical part of the survey and when they had a validated blood lead analysis. Lead exposures were collected through the environmental self-questionnaire. Table 1 gives an overview of the covariates studied in the ENNS lead survey. Characteristics of current and past work activities (type of activities, nature of work and duration of employment) were used to estimate whether subjects were occupationally exposed to lead.

Anthropometric measurements and blood samples were collected using standardized procedures at a health centre or at home by a nurse. For lead analysis, a 2 mL sample of heparin special oligoelements anticoagulated whole blood was obtained. After collection, blood specimens were centrifuged and aliquoted within a maximum of 8 h and remained frozen at −20 °C until analysis. Blood lead analyses were carried out in a central laboratory (Pasteur-Cerba laboratory) and measured by electrothermal atomic absorption spectrometry with Zeeman correction (Pineau et al., 2002). The limit of detection (LOD) was 2 μg/L and the limit of quantification (LOQ) was 10 μg/L. All specimens containing lead concentration greater than 100 μg/L were reanalyzed for confirmation. Internal and external quality control and quality assurance procedures were used to assure quality of the lead analyses.

Table 1
Covariates studied in the ENNS lead survey.

Individual characteristics	*Health characteristics*
Date of birth	Body weight and height
Sex	Osteoporosis
Marital status	Bone mass measurement
Size of household	Blood pressure
Occupational category	
Education level	*Environmental exposure*
Current or last work activity	Leisure activities linked to lead (especially home renovation with dust emission)
Professional status	
Household income level	Age of housing (white lead-based paint was used in France until 1948)
Feelings about household income	
Holiday within the last 12 months (Proxy of income level)	Type of drinking water
	Degree of urbanization
Detailed active smoking status	Geographical region
Passive smoking status (at work ; at home)	
	Occupational exposure
	Type of activities
Eating habits	Nature of work
Frequency of food consumption:	Duration of employment
Shellfish (crustaceans, mollusks); fish offal	
Quantity per day of food consumption:	
Fruits; vegetables; alcohol.	

Elevated BLL was defined as 100 μg/L or greater. In France this value defines actions to prevent lead poisoning in children (decree of the 5 February 2004 in the French regulation) and above this threshold adverse effects are clearly proven (suspected for adults). Participants with elevated BLL were contacted by a toxicologist to identify the origin of their exposure and to try to remove it.

All the sampling design characteristics (weights, stratification, stages) were used for both descriptive and multivariate analyses in order to produce unbiased estimates that were representative of the adult population living in France (Borgan, 1998). A calibration adjustment was performed with the CALMAR software using a truncated logit method (Sautory, 1993). The French census was used and calibration variables were sex, age (18–39, 40–59, 60–74 years) and educational level ("no certificate"; "high school"; "high school diploma/2-year university degree"; "bachelor degree or more"). The finite population correction (FPC), which can be used in case of sampling without replacement and sampling rate ≥0.15, was taken into consideration for the first-stage sampling units (UNSD, 2008).

Considering the criteria for eligibility, the sample design and the calibration adjustment, we considered that the study population was representative of the adult (18–74 years of age) population living in France.

In this study, there were no BLL data under the LOD. The percentage of values under LOQ (values between LOD and LOQ) was less than 4%. We retained the values measured by the laboratory even if their uncertainty was higher, considering that in the case of small censoring intensity (<15%), the method for treatment of left-censored data makes little difference (Zeghnoun et al., 2007). Proportions, arithmetic means and their standard error were used to present the characteristics of the population. Descriptive statistics of BLL (percentiles, median, geometric and arithmetic mean) were presented for the adult population living in France with and without subjects occupationally exposed to lead, and for subpopulations only without occupational exposure.

In the multivariate analysis, subjects occupationally exposed to lead were not included because the main objective of the analysis was to identify and quantify environmental risk factors (in the general population). Before applying methods of statistical inference, BLL were logarithmically transformed (log-BLL) to generate a distribution that was close to a normal distribution. We used a spline function with 3 degrees of freedom to assess the shape of the relationships between the log-BLL and the continuous explanatory factors. The association between the log-BLL and the explanatory covariates and the possible interaction terms was quantified by fitting a linear multivariate regression model. In order to check for the possible colinearity between the covariates included in the model, the correlation matrix between the regression coefficients was examined. Estimates of the regression coefficients of the model with their standard error and adjusted geometric means with their 95% confidence interval are presented. Statistical analyses were conducted using SAS version 9.1 (SAS Institute, 2004) and R version 2.6 (R Development Core Team, 2008).

3. Results

3.1. Participation

Of 5217 eligible households contacted, 3115 adults (aged 18–74 years) participated in the food consumption survey (participation rate = 59.7%) (Castetbon et al., 2009) and 2102 of these were included in the biochemical analyses (participation rate = 40.3%) and 2029 had a validated blood lead analysis.

3.2. Characteristics of the population

Table 2 shows socio-demographic characteristics of the adult population living in France and the distribution of environmental risk factors. The weighted mean age was 45 years. Nearly 89% of the population were born in continental France, 4% in other European countries, and 4% in Africa (Table 2). About 21% were factory workers, 18% worked as clerk and 21% in executive or intermediate professions. Two thirds of the population had taken a holiday within the last 12 months.

Fifty-six percent of the population were smokers or ex-smokers, and 44% had never smoked. Nearly 24% of the population were living in houses built before 1948, where white lead-based paints were potentially used. Around 23% had taken part in renovation works involving dust emission in houses built before 1948. Thirty per cent of the population consumed mainly tap water whereas 37% consumed mainly bottled water. The daily mean alcohol consumption in the population was 10.1 g/day. Around half of the population ate shellfish/crustaceans three times a month or more and 15% never ate it.

3.3. BLL distribution

A total of 1949 subjects had no identified occupational exposure and were used to describe BLL and to quantify environmental risk factor in the multivariate regression analysis.

Results including the population occupationally exposed to lead are presented only in the first line of Table 3. BLL were consistent with a log normal distribution (Fig. 1). The median value was 25 µg/L, and the 95th percentile was 73 µg/L. The blood lead GM was 25.7 µg/L [24.9–26.5]. Results including occupationally exposed subjects were the same for all percentiles and very close for geometric and arithmetic means.

GM of BLL were higher among men (30.0 µg/L [28.7–31.3]) than women (22.1 µg/L [21.2–23.0 µg/L]); all percentiles were also the highest for men (Table 3). All parameters of the distribution were increased with age except for the maximal value. The GM of BLL were 18.7 µg/L [17.8–19.6] in the youngest age group, 30.0 µg/L [28.2–30.5] in the intermediate age group and 39.3 µg/L [37.7–41.1] in the oldest age group. Highest 95th percentiles were found among people living in housing built before 1948 (91 µg/L) and among people who had several leisure activities potentially exposing them to lead, including renovation of housing built before 1948 (84 µg/L).

3.4. Elevated BLL

Twenty-nine participants had levels between 100 and 150 µg/L, 4 between 151 and 200 µg/L and 2 above 200 µg/L. The overall prevalence of elevated BLL in the population living in France (occupationally exposed to lead not included) was 1.7% [1.1–2.3%]. Elevated BLL increased with participant age: the prevalences of elevated BLL were 0.3% [0.3–0.3%] in the 18- to 39-year age group, 1.6% [0.5–2.7%] in the 40- to 59-year age group and 5.2% [3.4–7.1%] in the 60- to 74-year age group. Prevalence in men was more than three times higher than in women (respectively 0.8% [0.6–1.0%] and 2.7% [1.5–3.8%]).

The toxicologist identified various lead exposure sources for subjects with elevated BLL. Thirteen subjects had leisure activities which exposed them to lead such as sanding/scraping old paintwork and 15 participants were living in houses built before 1948. Two elevated BLL were explained by osteoporosis. No source of exposure was identified for seven subjects.

3.5. Multivariate analyses

Table 4 presents the parameters of the multivariate linear regression model, GM and their 95% confidence interval, adjusted on covariates significantly associated with BLL. The model identified 11 factors associated with BLL and one interaction, and

Table 2
Socio-demographic characteristics and environmental risk factors in the adult population living in France (Estimated mean values/percentages in the study population and sample size).

	N[a]	Weighted results (Se)[b]		N[a]	Weighted results (Se)[b]
Sex[c] (%)			**Holiday within the last 12 months (%)**		
Women	1271	50.8 (1.3)	Yes	1487	68.2 (1.1)
Men	758	49.2 (1.3)	No	532	31.8 (1.1)
Age[c] (years)			**Smoking status (%)**		
Mean	2029	44.9 (0.4)	Never smoked	936	44.0 (1.2)
Classes (%)			Former smokers	571	26.9 (1.1)
18–39	604	41.8 (1.1)	Smokers	522	29.1 (1.1)
40–59	988	39.6 (1.0)	**Age of housing (%)**		
60–74	437	18.6 (1.0)	Built after 1948	1400	69.7 (1.2)
Birth place (%)			Built before 1948	515	23.5 (1.1)
Continental France	1811	89.4 (0.7)	Don't know	114	6.8 (0.5)
Europe	62	3.9 (0.5)	**Leisure activities exposing to lead (%)**		
Africa	110	4.1 (0.3)	No leisure activity	1289	64.2 (1.1)
Others[d]	37	2.6 (0.2)	Leisure activities (not renovation)	267	12.5 (0.8)
Occupational category (%)			Renovation of old housing	126	5.7 (0.5)
Farmer	29	1.4 (0.3)	Renovation of old housing and another leisure activity	347	17.6 (1.0)
Artisan/independent retailer	46	2.3 (0.4)			
Executive	242	7.8 (0.4)	**Type of drinking water (%)**		
Intermediate profession	333	13.7 (0.7)	Mainly tap water	615	30.2 (1.1)
Clerk	227	18.1 (1.1)	Mainly bottled water	720	36.8 (1.4)
Factory worker	421	20.6 (0.9)	Both (bottled and tap water)	694	33.0 (1.1)
Retired	470	20.4 (1.0)	**Shellfish/crustacean consumption (%)**		
Others without occupation	261	15.7 (0.8)	Never	295	15.1 (1.0)
Alcohol consumption (g/day)			Twice a month or less	691	36.9 (1.3)
Mean	2029	10.1 (0.3)	Three times a month	748	34.5 (1.3)
			Once a week or more	295	13.6 (0.8)

[a]Sample size; [b]standard error of the percentage/mean; [c]calibrated covariate; [d]including America, Asia and French overseas territories.

Table 3
Distribution of blood lead levels (µg/L) in the adult population living in France (weighted results).

	Occupational exposure included	N[a]	GM [95CI GM][b]	AM (Se)[c]	Percentiles						
					10th	25th	50th	75th	90th	95th	Max
Overall	Yes	2029	25.9 [25.1–26.7]	31.8 (0.54)	12	17	25	39	58	73	334
	No	**1949**	**25.7 [24.9–26.5]**	**31.4 (0.56)**	**12**	**17**	**25**	**39**	**58**	**73**	**334**
Sex	No										
Women		1245	22.1 [21.2–23.0]	26.3 (0.56)	10	15	23	33	48	58	176
Men		704	30.0 [28.7–31.3]	36.7 (0.91)	12	19	29	48	66	85	334
Age (years)	No										
18–39		579	18.7 [17.8–19.6]	22.2 (0.68)	10	12	19	26	38	48	334
40–59		947	29.3 [28.2–30.5]	34.4 (0.80)	15	19	29	44	58	73	176
60–74		423	39.3 [37.7–41.1]	45.6 (1.11)	21	27	39	56	77	102	224
Smoking status	No										
Never smoked		907	23.7 [22.7–24.7]	28.8 (0.66)	10	15	25	37	50	62	334
Ex-smokers		545	29.4 [27.8–31.0]	35.5 (1.14)	15	19	29	46	63	81	176
Current smokers		497	25.5 [23.9–27.1]	31.4 (1.20)	12	17	25	39	60	75	224
Type of drinking water	No										
Mainly bottled water		688	24.1 [22.9–25.4]	29.7 (0.96)	10	15	23	37	54	75	224
Both (bottled and tap water)		668	25.5 [24.5–26.5]	30.2 (0.60)	12	17	25	39	55	64	176
Mainly tap water		593	27.8 [26.1–29.6]	34.7 (1.24)	12	17	27	46	62	81	334
Leisure activities	No										
No leisure activity		1249	23.6 [22.7–24.5]	28.4 (0.60)	10	15	23	37	52	60	176
Leisure activities (not renovation)		253	28.1 [25.3–31.1]	35.4 (2.21)	12	17	28	44	73	83	151
Renovation of old housing (only)		125	30.2 [26.8–33.9]	35.8 (2.23)	14	21	29	44	65	73	176
Renovation of old housing and another leisure activity		322	30.7 [28.5–33.1]	37.7 (1.49)	12	20	29	48	62	84	334
Age of housing	No										
Built after 1948		1347	25.1 [24.3–25.9]	30.3 (0.56)	12	17	25	39	54	70	176
Built before 1948		490	30.5 [28.6–32.4]	38.0 (1.34)	12	19	30	50	62	91	334
Don't know		112	18.5 [17.2–19.8]	21.3 (0.78)	10	12	19	23	35	46	112
Shellfish/crustacean consumption	No										
Never		281	21.9 [20.5–23.3]	25.9 (1.01)	10	15	21	31	48	59	106
Twice a month or less		664	23.9 [22.8–25.1]	29.9 (0.90)	10	15	23	39	56	66	334
Three times a month		722	28.6 [27.2–30.2]	34.9 (1.04)	12	19	27	46	64	78	224
Once a week or more		282	27.6 [25.7–29.7]	32.2 (1.06)	12	19	27	41	54	66	149

[a]Sample size; [b]geometric mean and 95% confidence interval for geometric mean; [c]arithmetic mean and standard error.

explained 42.1% of the BLL's variance. Age, sex, smoking status and alcohol consumption were the main predictors (50.6% of the explained variance together).

Log-BLL increased linearly with age ($p<0.001$) with an average increase of 25.8% [22.5–29.2%] (for BLL) each 10 years (Table 4). An interaction ($p<0.05$) was observed between sex and smoking status. BLL were higher in men than in women for each smoking status. In women, there were no differences between ex-smokers and current smokers.

BLL was also associated with birth place ($p<0.001$). People born in Continental France (25.3 µg/L [24.7–26.0]) had the lowest BLL. There were also differences associated with occupational categories: the highest BLL was found for farmers with GM = 30.0 µg/L [25.9–34.8]. People living in homes built before 1948 had higher BLL than those living in more recently built homes ($p<0.01$): GM = 28.0 µg/L [26.5–29.7] and 23.6 µg/L [22.8–24.5], respectively. BLL were higher for people who had done home renovations (especially renovations with dust emission in old houses) than those who did not have any leisure activities which exposed them to lead ($p<0.001$): GM = 28.4 µg/L [26.8–30.0] and 24.7 µg/L [24.0–25.4], respectively. BLL was significantly lower in people who had holidays within the last 12 months. Concerning eating and drinking habits, consumption of alcohol ($p<0.001$), tap water ($p<0.05$) and consumption of shellfish/crustaceans ($p<0.01$) were significantly associated with BLL. The Log-BLL increased linearly with alcohol consumption with an average increase of 5.3% [3.2–7.5%] (for BLL) for each 5 g a day consumed. Higher BLL were found among people drinking mainly tap water versus people mainly drinking bottled water (respectively GM = 27.1 µg/L [25.9–28.4] and 24.7 µg/L [23.6–25.9]).

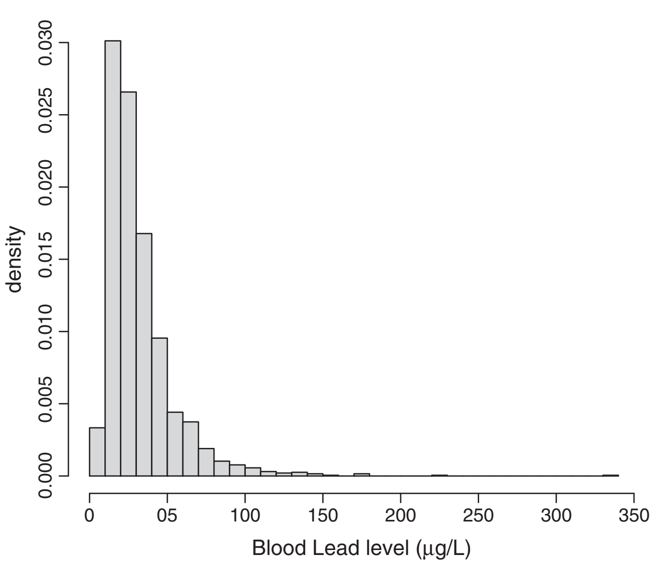

Fig. 1. Estimated distribution of BLL in the population living in France (18−74 years old).

4. Discussion

For the first time in France, data on blood lead levels were collected in a national representative survey for adults aged 18–74. The primary strength of ENNS lead survey is its ability to provide national estimates of BLL in the general population using a high degree of both protocol standardization and laboratory quality control. These data will be used as references to monitor BLL in the population living in France for next surveys and analytical investigations.

The rate of participation in the ENNS lead study was only 40.3%. Among households who refused to participate, some may be not eligible (they refused to answer to the eligibility questionnaire); thus, our participation rate is probably under-estimated. Certain characteristics such as interest in nutrition, healthy behavior and health status may have influenced the participation. The participation bias was accounted for by the calibration procedure according to national census data on age, sex and educational level. A previous analysis of a set of ENNS participants (which included the ENNS lead study participants) showed that the proportion of subjects who had not taken a holiday within the last 12 months and distribution according to birthplace, marital status and area of residence were mostly similar in the weighted sample and in the national census data, despite a few differences in age range (Vernay et al., 2009).

4.1. Temporal trends

A previous study conducted in 1995 (INSERM/RNSP, 1997) in France among men aged 18–28 years (mean age: 21.5 years) gave estimates of BLL distribution at a national level. The GM was 44.5 μg/L and the prevalence of elevated BLL (>100 μg/L) was 5.5%. In comparison, in ENNS lead survey the GM for men with a mean age of 21.5 years was 17.8 μg/L (prediction of the multivariate regression model for men aged 21.5 years) and the prevalence of elevated BLL (>100 μg/L) 0.2%. In 10 years a substantial decline was observed in the GM (−60%) and in the prevalence of elevated BLL (−95%) in France for men with a mean age of 21.5 years. These results indicate major progress in reducing lead exposure. We know that exposure due to leaded gasoline have continued to decline in the last 10 years (INSERM/InVS, 2008) and that the contribution of food and water consumption is probably lower today than in the past (Leblanc et al., 2005; Glorennec et al., 2007). Other lead exposure may have also declined. Nonetheless, lead remains present, because of its wide dispersion over many decades and its continuing industrial uses. The decrease of BLL in older subpopulations, who are still more heavily influenced by past exposure as a result of the mobilization of lead stored in bone, is probably lower.

4.2. Comparison with others countries

Distributions of BLL from population studies in Germany (Becker et al., 2002) and the Czech Republic (Batariova et al., 2006) were consistent with the current distribution in France. The median in ENNS lead survey (25 μg/L) was slightly lower than in Germany (31 μg/L) and Czech Republic (33 μg/L) and the 95th percentile in the three countries was similar (73 μg/L in France, 71 μg/L in Germany and 72 μg/L in Czech Republic). Parameters of the distribution of BLL from the United

Table 4
Parameters of the multivariate linear regression model (log-BLL) and adjusted geometric means (μg/L).

		Adjusted geometric mean [a] [95% CI][b]	β (Se)[b]	p
Age (years) % increase of BLL for 10 years [a]		25.8% [22.5–29.2%]	0.023 (0.001)	<0.001
Sex and Smoking status				
Men	Never smoked	24.8 [23.1–26.6]	Ref.	<0.05
	Ex-smokers	25.8 [24.1–27.6]	0.04 (0.04)	
	Current smokers	30.5 [28.8–32.3]	0.21 (0.05)	
Women	Never smoked	21.2 [20.2–22.4]	Ref.	
	Ex-smokers	23.2 [22.0–24.6]	0.09 (0.10)	
	Current smokers	23.5 [21.9–25.1]	0.10 (0.10)	
Occupational category				
Factory workers		27.1 [25.5–28.8]	Ref.	<0.01
Farmers		30.0 [25.9–34.8]	0.10 (0.08)	
Artisans/independent retailers		24.4 [22.3–26.7]	-0.11 (0.05)	
Executives		25.4 [24.2–26.5]	-0.07 (0.04)	
Intermediate professions		25.2 [24.0–26.4]	-0.07 (0.04)	
Clerk		25.3 [23.9–26.7]	-0.07 (0.04)	
Retired		23.8 [22.3–25.3]	-0.13 (0.05)	
Others without professional activities		27.6 [25.8–29.5]	0.02 (0.04)	
Holiday within the last 12 months				
Yes		25.1 [24.5–25.8]	Ref.	<0.05
No		26.8 [25.6–28.1]	0.07 (0.03)	
Birth place				
Continental France		25.3 [24.7–26.0]	Ref.	<0.001
Europe		28.2 [24.4–32.7]	0.11 (0.07)	
Africa		28.0 [25.5–30.8]	0.10 (0.05)	
Others[c]		29.4 [27.3–31.7]	0.15 (0.04)	
Age of housing				
Built after 1948		23.6 [22.8–24.5]	Ref.	<0.01
Built before 1948		28.0 [26.5–29.7]	0.12 (0.03)	
Don't know		24.9 [23.2–26.8]	0.00 (0.04)	
Leisure activities (lead exposure)				
No leisure activity		24.7 [24.0–25.4]	Ref.	<0.001
Leisure activities (not renovation)		26.3 [24.6–28.1]	0.06 (0.04)	
Renovation of old housing (only)		27.2 [24.8–29.9]	0.10 (0.05)	
Renovation of old housing and another leisure activity		28.4 [26.8–30.0]	0.14 (0.03)	
Type of drinking water				
Mainly bottled water		24.7 [23.6–25.9]	Ref.	<0.05
Both (bottled and tap water)		25.4 [24.5–26.3]	0.03 (0.03)	
Mainly tap water		27.1 [25.9–28.4]	0.09 (0.04)	
Alcohol (g/day) % increase of BLL for 5 g of alcohol consumed per day [a]		5.3%[3.2–7.5%]	0.010 (0.001)	<0.001
Shellfish/crustacean consumption				
Never		23.2 [22.1–24.4]	Ref.	<0.005
Twice a month or less		26.0 [25.0–27.0]	0.11 (0.03)	
Three times a month		26.0 [25.0–27.1]	0.11 (0.03)	
Once a week or more		26.5 [25.1–27.9]	0.13 (0.04)	

[a]Geometric mean and % increase were adjusted on age, alcohol consumption, birth place, occupational category, holiday within the last 12 months, type of drinking water, leisure activities (lead exposure), age of housing, shellfish/crustacean consumption frequency, sex and smoking status; [b]estimate of the coefficient and standard error; [c]including America, Asia and French overseas territories

States (CDC, 2005) (GM = 17 μg/L and 95th percentile = 46 μg/L) were systematically lower than those of the ENNS study and other European studies. This is probably in connection with the fact that lead in gasoline was banned earlier in the United States than in Europe. In the United States the sale of unleaded gasoline started in the 1970s (from 1976 to 1990 the amount of lead used in gasoline decreased more than 99.8%), whereas in France it began only in 1990s. In 1996, the Clean Air Act banned the sale of leaded fuel for use in on-road vehicles in the US whereas in Europe it was only in 2000 (directive 98/70/CE). BLL in the US will probably be lower than European BLL until lead concentration due to past exposure from lead gasoline has totally disappeared.

4.3. Factors explaining BLL

The findings from the ENNS lead survey highlight that BLL are still strongly influenced by age, sex, smoking habits, and alcohol consumption. Together, these four covariates contribute to more than 51% of the total explained variations. Other factors were found to be associated with BLL: occupational category, holiday within the last 12 months, birth place, age of housing, leisure activities, type of drinking water, and shellfish/crustacean consumption.

Log-BLL increased linearly with age. Indeed lead accumulates in the body with age (Brody et al., 1994; Pirkle et al., 1994; Pirkle et al., 1998; Fréry et al., 2009), especially in bone (Nilsson et al., 1991). Nevertheless, a part of the difference observed in GM between the 18–39 years aged group (18.7 [17.8–19.6]) and the 60–74 years aged group 39.3 [37.7–41.1] probably resulted from a higher level of exposure in past years.

In our study, alcohol consumption was, after the age, the most important covariate influencing BLL (Fréry et al., 2009). There are uncertainties concerning the source of contamination of alcohol. Concerning wine, mean lead levels have decreased in recent decades, from 60 μg/L in the 1990s to 15 μg/L in 2004 (INSERM, 1999; INRA, 2004). A possible source of contamination may be persistent lead arsenate, which was widely used as a pesticide in fruit and wine cultivation until its banning in 1973 (decree of the 24 may 1973 in the French regulation).

As expected(Brody et al., 1994; Pirkle et al., 1994; Staessen et al., 1996; Pirkle et al., 1998; INSERM, 1999; Fréry et al., 2009), BLL were consistently higher in males than in females, with a difference of about 3.5 μg/L. This gap is probably due to higher lead exposure in men. Items from the environmental questionnaire may estimate lead exposure imperfectly and differently for men and women (a part of the exposure may also be unlisted): the sex covariate would be a proxy of these covariates. Differences in metabolism between males and females, particularly hormonal differences, could be another explanation (IPCS, 1995; Batariova et al., 2006). Young or premenopausal women would retain lead in bone more avidly or release lead in bone more slowly than do men, and consequently, BLL would be higher for men for some ages. This difference is lost for postmenopausal women. This is potentially associated with low oestrogen levels in postmenopausal women (Popovic et al., 2005). Nevertheless, we found no interaction between age and sex.

Smoking status is still consistently associated with BLL and remains a significant source of lead exposure (Fréry et al., 2009). The precise sources and mechanisms of the observed overexposure of smokers remain controversial. Possible explanations could be the facilitated transportation of airborne lead into the lungs by smoke particles (Wietlisbach et al., 1995) or lead intake by more frequent hand-mouth contact (Wietlisbach et al., 1995; Weyermann and Brenner, 1997). Possible explanation for the interaction between sex and smoking status could be the gender difference relative to smoking behavior (i.e. women inhale smoke less than do men) (Melikian et al., 2007; Gan et al., 2008).

Age of housing is still a potential source of lead exposure (Brody et al., 1994; Pirkle et al., 1994; INSERM/RNSP, 1997; Pirkle et al., 1998; Huel et al., 2002). In France, housing built before 1948 can be a source of lead exposure. Indeed white lead-based paint was still used in France until 1948 even though regulations banning the use of white lead-based paint were existed from early the 19th century. We found that BLL were, on average, 2.9 μg/L higher in people living in houses built before 1948.

Leisure activities are also a possible source of exposure to lead (INSERM/RNSP, 1997). Of the multiple leisure activities (such as shooting, painting or pottery), renovation of housing built before 1948 with dust emission (scraping of doors, etc.) is known (IPCS, 1995) to be a high source of lead exposure through the ingestion/inhalation of dust. In our study, leisure activities with possible exposures to lead effectively increased BLL. The increase was greater if the activity was renovation of old housing. When people had several such activities, including renovation of old housing, the difference was the greatest (3.5 μg/L). Among people with elevated BLL, we often found that they had undertaken renovation of old housing. Although white lead-based paint has not been used for over 60 years, lead exposure associated with residual lead paint in old housing is still possible in France.

Drinking water is a potential and controversial source of lead exposure (Moralez et al., 2005; Glorennec et al., 2007; Fréry et al., 2009). Contamination of drinking water may occur through plumbing containing lead such as pipes, solder, pipe fittings and sediments. In the past, lead was widely used for the fabrication of pipe with low diameter (public branch pipe, and private segments inside the buildings and housing). In France, lead was progressively banned from public segments from 1960 and from private segment from 1950. In 1990, 34% of housing still contained lead pipes and in 2000, 3.4 million lead-based public service lines were still used to provide water to buildings. The European regulation (directive 98/83/CE) for lead in water stated a threshold of 10 μg/L in 2013. Thus, since the late 1990s, the lead risk management policy aims to eliminate lead in public branch pipe and pipe inside buildings. In our study, BLL were on average 2.2 μg/L higher in people who mainly drank tap water and no interaction was found between the consumption of drinking water and the age of housing. Even if BLL were statistically associated with consumption of drinking water, this factor was a low contributor to the total explained variations (less than 1.5%).

As is widely known, socioeconomic context can promote lead exposure (Brody et al., 1994; Pirkle et al., 1994; Pirkle et al., 1998; Muntner et al., 2005; McKelvey et al., 2007). Unfortunately, there were numerous missing data in the income level covariate (5.7% including “don't know” and “don't want to answer”). Participants were also asked if they had taken one or more holiday trips lasting four nights or more during the past 12 months, shown in previous studies as being strongly associated with household income (Le Jeannic and Ribera, 2006; Vernay et al., 2009). This covariate is easier to collect during a face-to face interview, as the French population is highly unlikely to reveal its income. We found that this covariate was negatively associated with BLL. Occupational category was also associated with BLL. Farmers were more likely to have higher BLL. This is probably due to an exposure to lead potentially greater than in other occupations.

People born in continental France were found to have lower BLL than people born elsewhere. In some countries (i.e. North Africa), traditional ceramic cookware and crockery (used for storage or cooking) could be a source of lead exposure (Nriagu et al., 1996; Lynch et al., 2008), particularly when cooking with acidic foods, because low pH enhances the leaching process. Traditional ethnic medicines and cosmetic (kohl or surma) have also been identified as other sources of lead exposure (Alkhawajah, 1992; Al-Ashban et al., 2004). Others sources are probably still higher in some countries than in France (leaded gasoline may still be used, food may be contaminated, etc.).

It is of current knowledge that crustaceans and mollusks are among the food products the most contaminated by lead (DGS, 1995;

Leblanc et al., 2005) and that regular consumption of shellfish/crustaceans increased BLL (McKelvey et al., 2007; Fréry et al., 2009). As a matter of fact, in this study, people never consuming shellfish/crustaceans food had lower BLL than consumers.

5. Conclusion

The ENNS lead survey provides estimates of BLL at a national level. In this study, the geometric mean of BLL in the adult population living in France was 25.7 µg/L and the overall prevalence of elevated BLL was 1.7%. BLL were influenced by age, sex, smoking habits, and alcohol consumption. The 95th percentile is still high among people who have undertaken renovation of old housing. In 10 years, we observed a substantial decline in GM and elevated BLL in young men. The distribution was quite similar to that observed in other European countries (Germany and Czech Republic). Such data will be useful for the determination of reference values in France and for future temporal comparison.

Competing interest declaration

The authors declare they have no competing financial interests.

Acknowledgements

ENNS was supported by the Institut de veille sanitaire (InVS), the Université de Paris 13, and the Caisse nationale d'assurance maladie des travailleurs salariés (CnamTS). We thank the dietitians, nurses and physicians, the staff of Health Examination Centres of CnamTS, the laboratory Pasteur-Cerba, which contributed to data collection and biochemical analyses.

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