High lead level in the Alps in XIXth century, learning from the analysis of 138 historical hair stands

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In honor to Dr. Jules Carret (1844-1912), Bernard Jégou (1951-2021) and Olivier Thomas (1951-2021)

Highligths

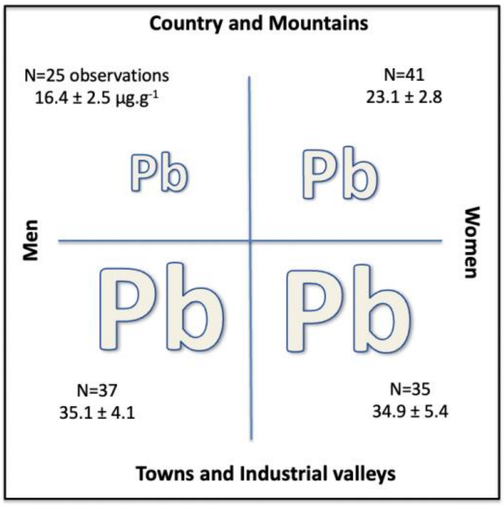
- The analysis of 33 elements was carried out on 138 historical hair strands sampled around 1880 in the French Alps.
- The hair lead level (HLL) was higher than values reported in literature.
- HLL was depending on samples localization, and higher in town and industrial valleys than in mountains area and countryside

Abstract

Analysis of hair is known to provide useful information about environmental and toxic exposures. Very little historical use has been made of this type of investigation. Here we study 138 human hair samples from 19th century in France.
In order to examine the potential association between contamination and historical health impacts, we characterized contamination by 33 elements in a set of hair strands sampled during the last quarter of the 19th century in the Savoy region of France.
After a selected washing step on 138 hair strands conserved at the Museum National d'Histoire Naturelle in Paris (France), we assessed the presence of inorganics by ICP/MS, and lead level was higher than values reported in literature. We then compared concentrations and distributions between women and men, sampling locations and crossing gender and geographical origin.
Hair lead level was high throughout Savoy at the end of the 19th century: significantly higher for people living in towns or industrial valleys, and lower for those of countryside and mountains areas. Environmental and economic changes (industrialization and urbanization with water adduction and leaded paints), living habits (kitchenware, cosmetics, wine, and tobacco), and local features (mines exploitation, railroad development, and industrialized narrow valleys) could be envisaged for explaining the level of lead contamination. In the same period, the two main industrial valleys of Savoy (Maurienne and Tarentaise) had high rates of endemic goiter and cretinism and among the highest hair lead levels. Other lines of

evidence will need to be explore to investigate a possible link between historical Pb exposure and goiter in the study area.

Graphical abstract



1 Introduction

With the development of modern anthropology in France during the XIXth century, expeditions or specific campaigns collected items such as human skulls, skeletons, bones, and hair from all over the world. One of the first museum dedicated to these types of collections was created in Paris by Paul Broca (1824-1880) (Vallois 1940), the founder of the French physical anthropology (Ashok, 2017); These collections were then included in 1937 as a part of the Museum National d'Histoire Naturelle (MNHN) in Paris (France). Substantial work has taken place on the characterization of skulls and bones from this collection, but until now, no one had analyzed the human hair samples. This might seem surprising, given that human hair samples are widely used today for biomonitoring current exposure to chemicals (Grandjean 1978, Appenzeller and Tsatsakis 2012, Pozebon et al. 2017) and have also been used to document diets in ancient human populations (Macko et al. 1999). Human hair is a stable matrix that presents numerous advantages for human biomonitoring, such as easy collection, low cost, easy transport and storage, information about short- and long-term exposure, and renewable (Baez et al 2000; Kintz et al 2007; Esteban and Castano 2009). The main disadvantages of using this matrix is the difficulty in correlating hair and blood contamination and in differentiating between external and internal exposure, that needs an efficient washing step.

This biological material has largely been ignored for the purpose of retrospective environmental analysis probably because of the rarity of historical collections and of the intrinsic difficulty of access to documented collections of them.

The present study had the following objectives: (i) to examine the inorganics concentrations in historical hair strands, (ii) if some differences can be shown depending on gender or sampling locations, to look for potential factors of contamination, and (iii) then assess a possible relation between the highest concentrations of hair contamination and rates of endemic disease historically recorded in samples location.

2 Material and methods

2.1 Hair samples

Before our study, the human hair samples collection, managed by Dr. Latteux (1840-1916) in the Broca Museum (Vallois 1940) and nowadays located in the Museum National d'Histoire Naturelle (MNHN) in Paris, had never been analyzed. This collection is composed of more than 200 hair strands from various parts of the world, including a set of 138 strands from the Savoy region, located in the heart of the Northern French Alps. For this study, our assumptions about the selection of individuals for hair sampling are based on the available historical data, which show that these samples were collected during the period when anthropological investigations had strongly begun in France, under the leadership of Paul Broca in the second half of XIXth century. Volunteers (often medical doctors) in metropolitan France, and French colonies, provided body and face morphometric data and sometimes hair samples. For example, Dr Jules Carret in Chambery (1844-1912), conducted anthropological investigations in Savoy in 1880-1882, during the board of review of male conscripts (Billy 1962, De Mortillet 1892). From what is generally known, women could also have been approached during medical examinations for pregnancy following or hospital stays. Obviously, the way of hair sampling operation is not precisely known, but, given that the main operator had a scientific background (Dr Carret) and was guided by Broca's recommendations (Carret 1882, Broca, 1865), hair samples should have been taken and handled carefully before sending or bringing them to the Broca museum in Paris for microscopic analysis by Dr. Paul Latteux, an early specialist in this technique (Latteux 1877). The strands were stored in small plastic tubes, affixed to cardboard sheets that identified them (Figure 1), and further protected in a box. The sampling location (14 collection spots in

Savoy) and gender information (76 women and 62 men) were recorded on the sheet. Based on careful examination of the records of Dr. Latteux's activities (Latteux 1877; Broca et al. 1877) the hair samples of Savoy were most likely collected around 1880-1882, probably by Dr. Carret himself. The sampling locations, written on the cardboard sheets, were principally the main towns of Savoy (Chambéry, Annecy, Aix les Bains, Albertville), valleys (Maurienne, Tarentaise, Arve), and several other sites (of countryside and mountains area). 4 to 28 hair samples were collected from each site (Figure 2). To adhere to MNHN guidelines (namely respect of collections integrity) and meet the study needs, hair subsamples of the most important hair strands of this collection were taken on site, all weighing less than 20 mg. Each strand was carefully placed in an individual envelope, duly identified, grouped and transported to our laboratory for analysis.

Figure 1: Cardboard with the hair strand removed from its plastic tube, and information (with permission of MNHN, Paris)

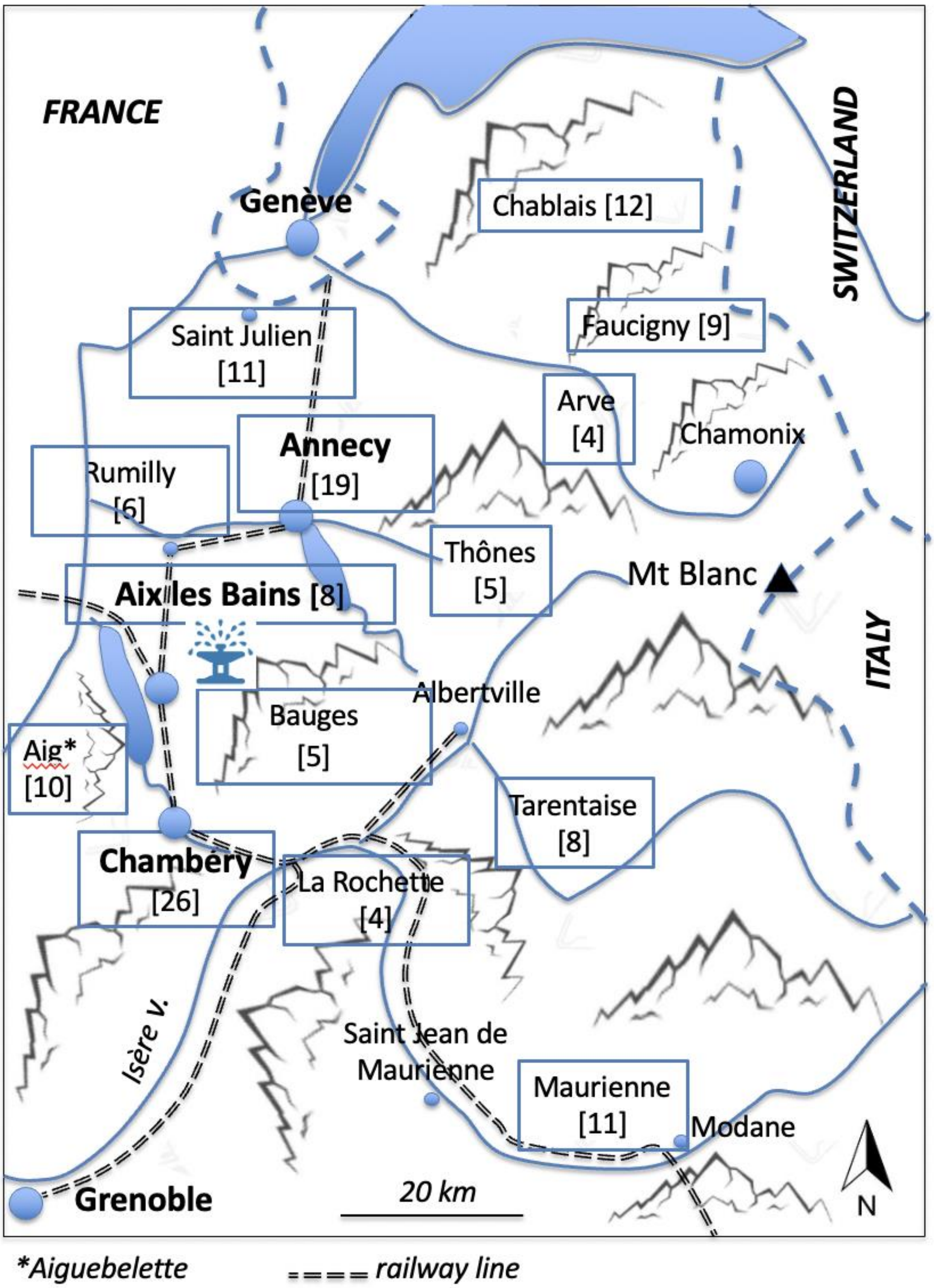


Figure 2: Schematic map of Savoy with railway lines (= = =) in 1875 and the 14 collection spots (with the number of hair samples collected in brackets).

2.2 Geographical context: Savoy region

The Savoy was linked to France in 1860; at that time its population was around a half million inhabitants, with as its largest towns Chambéry (population ~ 20,000), Annecy (~ 10,000), and Aix les Bains (~ 3,000). At the period of hair collection, the local economy was gradually becoming more open to commercial exchange with the rest of France and Italy, thanks to the development of the main railway lines constructed between 1856 and 1879. In 1871, the Frejus tunnel was bored at the end of the Maurienne valley for a railway link between Chambéry and Turin (Italy). Among industrial activities, foundries were installed in deep valleys (Maurienne and Tarentaise) because of the presence of numerous mining sites, particularly in the high mountains dominating the Savoy valleys (Raffaelly 2020). Iron ore, copper, silver, and lead ores were extracted (Rossi and Gasquet 2017). The collection spots and the railway lines (Figure 2) suggest that the principal collection sites for hair sampling were chosen for their ease of access (towns, valleys) and thus were often close to mining areas.

2.3 Analytical method

The chemical elements in the historical hair samples were analyzed by inductively coupled plasma/mass spectrometry (ICP/MS) after digestion/mineralization using a new washing procedure developed for the purpose by Verrey et al. (2019). ICP/MS being the main analytical method for quantitative ultra-trace elemental analysis, Pozebon et al. (2017) reviewed a huge number of works proposing methods for the analysis of around 30 elements in hair. For our study, 33 elements were analyzed: Li, Be, Na, Mg, Al, P, K, Ca, V, Cr, Fe, Mn, Cu, Zn, As, Se, Sr, Mo, Ru, Cd, Sb, Cs, Ba, La, Ce, Nd, Gd, Lu, Tl, Pb, Bi, Th, and U. Given that historical hair samples were collected 140 years ago, and then handled, transported and stored under undefined conditions, an efficient washing protocol was mandatory for removing natural compounds (such as sweat, sebum, and skin cells), care products, and external contaminants already present during the sampling step or deposited afterwards. These include tobacco smoke products, one of the main external sources of contamination of historical hair strands between sampling and analysis (Cooper et al., 2012; Rustermeier et al. 2002; Pappas et al., 2006; Lazarevic et al. 2012).

All of the recent washing methods described in the literature involve several successive steps of treatment with selected reagents (surfactant, chelator, solvent, water, and nitric acid). For this work, the method proposed by Verrey et al. (2019), based on a mix of two procedures (Batista et al. 2009; Eastman et al. 2013) was used on historical samples. The protocol is based on three stages of washing (Triton 0.5%, nitric acid 6.7%, and hydrochloric acid 2%) and takes less than 25 minutes. The application of this method to historical hair samples, with its two acid washing stages, resulted in a removal rate more than 50% greater than other washing methods (Verrey et al. 2019), even if the total washing time is shorter than with other procedures (the addition of the hydrochloric acid washing step could possibly explain this gain). At the end of the washing step, hair strands were kept in a 50 °C oven until dry.

For the mineralization step, around 20 mg of dry washed hair sample was taken, weighed, and placed in a 15-mL polypropylene tube with 0.5 mL of 67% nitric acid solution. The tube was closed with screw caps and placed in an ultrasound bath for 15 minutes and then in a graphite oven at 90°C for 6 hours. After cooling, 10 mL of UHQ water was added and the tube replaced in the ultrasound bath for 15 minutes. Sample solutions were then transferred into 15-mL polyethylene tubes and closed until analysis.

In addition, we also analyzed some raw samples (without washing) after their digestion (Kempson and Skinner 2012) in order to compare the values obtained on raw and washed samples.

The ICP/MS analysis was carried out thanks to an Agilent Technologies 7500ce spectrometer (Santa Clara, CA, USA). Samples were delivered by the autosampler (CETAC (Waltham, MA, USA) ASX-520) to a MicroFlow nebulizer and a Scott nebulization chamber. The Agilent MassHunter software controlled the entire system. The analytical parameters were configured as follows: sample feed rate of 0.3 mL/min, RF power of 1550 W, chamber temperature of 2°C, and plasma gas flow of 15 L/min. The limit of quantification of the 33 elements were the following (with LOQ in µg.g-1 in parentheses): Al (10), As (0.2), Ba (0.5), Be (0.05), Bi (0.05), Ca (100), Cd (0.05), Ce (0.125), Cr (0.5), Cs (0.05), Cu (1), Fe (2.5), Gd (0.025), K (50), La (0.1), Li (3.125), Lu (0.05), Mg (25), Mn (0.5), Mo (0.125), Na (50), Nd (0.025), P (2.5), Pb (0.1), Sb(0.2), Se (1), Sr(0.25), Ru (0.05), Th (0.1), Ti (0.05), V(0.05), U (0.025) and Zn (5).

The analysis were validated according to protocol and statistical tests described in the NF T 90-210 French standards (AFNOR 2009). Some samples required dilution for inclusion in the calibration range. Two reference materials were used (IAEA-086 and CRM- 81002b), and the laboratory was involved in five inter- laboratory tests (ILTs) organized by Institut National de Santé Publique du Québec (INSPQ) to evaluate the method. Results of ILTs were in Table 1. For Pb, the use of CRM material served as an internal control and showed good agreement with an effective measurement of 3.94 µg.g-1 (RSD 11%) for a reference value of 3.83 ± 0.18 (Verrey et al. 2019).

Table 1: Results of the laboratory (concentration $\mu g.g^{-1}$ and bias %) of 5 ILTs organized by INSPQ for Cu, Zn and Pb in hair samples.

	Cu		Zn		Pb	
ILTs	Conc. ($\mu g.g^{-1}$)	Bias (%)	Conc. ($\mu g.g^{-1}$)	Bias (%)	Conc. ($\mu g.g^{-1}$)	Bias (%)
1	19.3	4%	212	-5%	1.50	-2%
2	57	-4%	306	-5%	2.9	-7%
3	139	4%	304	9%	10.9	-3%
4	55	9%	399	5%	1.8	7%
5	66	3%	311	4%	11.0	-2%

Before implementing historical hair analysis, the question of the relevance of the washing method shall be asked. Another recent comparison of washing methods before ICP analysis, led by Aloupi et al. (2020) on feathers, (which the keratine composition is very close to those of hair), confirmed that the one developed and used for this work (Verrey et al. 2019), based on a sequence of three steps of detergent or acid washing (Triton, nitric acid, and hydrochloric acid) was shown to be more efficient for the inorganic element analysis of hair, than those that included the use of surfactants and organic solvents (Verrey et al. 2019).

Finally, in a recent study (Gil-Jimenez et al., 2020) used feathers and hair of wild life as tools for non-destructive pollution exposure assessment in a mining site of the Iberian Pyrite Belt.

2.4 Study design

After washing and ICP-MS analysis of the historical samples, elements present in all samples are retained. The main observation being that lead level is often high in hair samples, statistical comparisons by gender, geographical origin and crossed are carried out.

2.5 Statistical analyses

In order to examine the potential relations between analytical results, a simple statistical analysis was carried out with Prism 7 (Graphpad software). The following tests were performed on raw and data grouped by gender or geographical origin: D'Agostino and Pearson normality test, ROUT outlier identification, and the Kruskal-Wallis nonparametric test for ANOVA. Finally, we used two nonparametric t-tests to compare the distributions, the Mann-Whitney, which detects shifts in the median, and the Kolmogorov-Smirnov, which detects differences in the shape of the distribution.

3. Results

3.1 Concentration of elements

Table 2 reports the concentrations of elements founded in the historical hair strands. Because most of samples analyzed showed elements values under the limit of quantification (LOQ), the Table 2 includes only the 6 elements present in all samples after washing: P, Ca, Fe, Cu, Zn, and Pb. Alkaline elements and some rare elements (lanthanides and actinides) were not detected here.

The differences in the values of their arithmetic and geometric means suggest that these distributions are not Gaussian, as confirmed by the results of the D'Agostino and Pearson normality test. The maximum concentration values for these elements were close to or exceeded 50 $\mu g.g^{-1}$.

Finally, in absence of a washing stage for the set of historical hair samples studied, the ratio between mean concentrations of washed vs raw samples varied from 1.4 for Ca, to 4.25 for

Pb (119.7 versus 28.07 µg.g^{-1}), a difference related to the strong external contamination between sampling and analysis.

Table 2: Characteristics of results for the 6 elements analyzed present in all historical hair samples (concentrations in µg.g^{-1}).

Element	Mean	Median	Min[a]	Max[a]
P	67,3	59,6	37.95	115.5
Ca	334,6	305	131,5	1263
Fe	29,8	18,5	7.5	312
Cu	9,7	8,5	4.82	47.5
Zn	84,8	81	21.5	158
Pb	28,1	22,3	1.6	135.5

[a]Min: minimum. Max: maximum

For elements of table 2 (P, Ca, Fe, Cu, Zn, and Pb), a gender comparison revealed no significant difference between the distributions of results for the women and the men (Table 3).

Table 3: Comparison of the distributions of element concentrations in the historical hair samples of women and men (in µg.g^{-1}). (Elements present in all hair samples)

Element	Mean W[a]	Median W	Min W	Max W	Mean M[a]	Median M	Min M	Max M	M-W[b] *p*	K-S[b] *p*
P	66.55	64.5	39	115,5	68.3	66.5	37,95	103	0.5602	0.8406
Ca	340.5	322.5	155	873	327.4	262.5	131,5	1263	0.0974	0.0591
Fe	30.28	19.0	7,5	312	29.42	17.5	8	254	0.9318	0.7501
Cu	9.606	8.55	5,05	33,75	9.85	8.30	4,8	47,5	0.7910	0.9301
Zn	80.11	75.0	21,5	158	90.67	89.8	34	151	0.0520	0.1093
Pb	28.5	21.57	1,6	135,5	27.53	22.75	1,6	122,7	0.9278	0.9815

[a] W: Women (76 samples), M: Men (62 samples)

[b] p values of M-W Mann-Whitney test/K-S Kolmogorov-Smirnov test

3.2 Hair lead level

It could be interesting to compare the concentrations of inorganics in our 19th century samples with values of hair contamination reported in literature. If there exist some studies on inorganics levels in hair focusing on contemporary people or on historical samples (mummies), they are unfortunately not fully comparable in terms of samples characteristics (number, age, gender, geographical location). For example, in their review of reference values of elements in hair, Mikulewickz et al. (2013) carried out a meta-analysis on hair analysis results obtained by ICP/MS after a washing step less efficient than the protocol used for this study. 52 studies were considered among which only 5 met the IFCC criteria and inclusion criteria (international federation of clinical chemistry) (Poulsen et al, 1997), among which 5 elements and 120 observations or more. All studies included in this meta-analysis referred to young people less than 18 years, but reference values of elements are very close to the ones of the present study, with the notable exception of lead, lower (1 $\mu g.g^{-1}$ or less for the lower range, against 1,6 $\mu g.g^{-1}$ and more for the studied set of hairs) (Senofonte et al., 2000, Dongarra et al. 2011, Park et al. 2007, Carneiro et al., 2011). This consideration could be completed by the results obtained for 10 contemporary hair strands sampled in 2016 and analyzed in our laboratory with the method used here (Verrey et al. 2019). If the results for other elements were close to the data of the present study, the hair lead level (HLL) was around 0.2 $\mu g.g^{-1}$. In a recent study on the exposure of street sweepers to cadmium, lead, and arsenic in dust based on variable exposure duration in zinc smelting district, Northeast China, Li et al, (2021) reported a hair lead level mean of 20.2 $\mu g.g^{-1}$ for 62 adults workers.

Lead was analyzed in hair samples of 107 people living around two industrial sites (a factory manufacturing storage batteries and a lead-cadmium plant) in Russia (Revich 1994). The maximum HLL analyzed was 48.3 µg.g-1 for children, after surfactant hair washing less efficient than the washing method used for the present study. Other works have reported mean HLL of 12 µg.g-1 for 33 street vendors in Istanbul (Furman and Laleli 2000), of 15.5 µg.g-1 for 222 children living in two Sardinian towns (Sanna et al. 2003), and of 18.7 µg.g-1 for 24 people living close to oilfields (Pragst et al. 2017). In a recent study on lead concentrations in hair of hospital workers, Mao-Chin and Chang (2021) funded that lead concentrations in the hairs of the radiological technologists with lead shielding, were significantly higher than those in the administration staffs, without shielding (0.72 ± 0.51 vs. 0.19 ± 0.27 μg.g^{-1}, $P < 0.001$). However, if these HLL remained rather low, an increase is observed, associated with environmental lead concentration (Mao-Chin and Chang, 2021). Regarding historical results, one study was carried out by Bartkus et al. (2011), from hair samples taken from mummies of Chinchorro individuals living in the Atacama Desert of Chile around 5000–1500 B.C. 49 samples of mummies hair were analyzed using laser abrasion LA-ICP-MS. The maximum hair lead level founded was 13.8 μg.g-1. Finally, bone samples have also been used as a biomarker for human exposure to Pb in historical/anthropological studies (Swanston et al. 2018).

3.3 Human hair lead levels distribution

Human hair lead levels were much higher for the 138 historical samples in Savoy than for other HLL reported in literature and did not differ for men and women (Table 3). Because the Savoy region is characterized by high mountains (including Mont Blanc, 4807 m) and deep industrial valleys, the HLL distribution was assessed according to 4 different geographical categories (Figure 2):

- **T**: **T**owns (n samples =53): Chambéry (n=26), Annecy (n=19), and Aix les Bains (n=8)
- **V**: Industrial **V**alleys (n=19): Tarentaise (n=8) and Maurienne (n=11)
- **C**: Small villages and **C**ountryside (n=35): Saint Julien (n=11), Rumilly (n=6), La Rochette (n=4), Aiguebelette (n=10), and Bonneville (n=4)
- **M**: **M**ountain areas (n=31): Chablais (n=12), Faucigny (n=9), Aravis (n=5), and Bauges (n=5).

The mean HLL values were 35.8 μg.g^{-1} for the towns, 32.6 μg.g^{-1} for the industrial valleys, 17.2 μg.g^{-1} for the small villages and countryside, and 23.9 μg.g^{-1} for the mountain areas. The towns and valleys (T-V), with means exceeding 30 μg.g^{-1}, and the countryside and mountains (C-V), with lower means around 20 μg.g^{-1}, had significantly different distributions: a *p* value of 0.0002 according to the Mann-Whitney t test and 0.0032 with the Kolmogorov-Smirnov t-test. Accordingly, we continued to group together HLL in towns and valleys (T-V) and compare them with the group of countryside and mountain areas (C-M) to examine if HLL varied according to gender. Table 4 presents the main characteristics of the four resulting classes, crossing geographical origin and gender.

Table 4: Characteristics of classes: Women (T-V), Women (C-M), Men (T-V), and Men (C-M), Pb concentrations in $\mu g.g^{-1}$

Classes	Number of samples	Mean	median	min	max
Women (T-V)	35	34,9	24,9	6,4	135,5
Women (C-M)	41	23,1	20,45	1,6	72
Men (T-V)	37	35,1	26,6	2,1	122,7
Men (C-M)	25	16,4	14,4	1,7	43,9

The distributions of the 4 classes were compared with a nonparametric unpaired ANOVA (Kruskal-Wallis) test, which revealed a statistically significant difference between distributions (p = 0.0013).

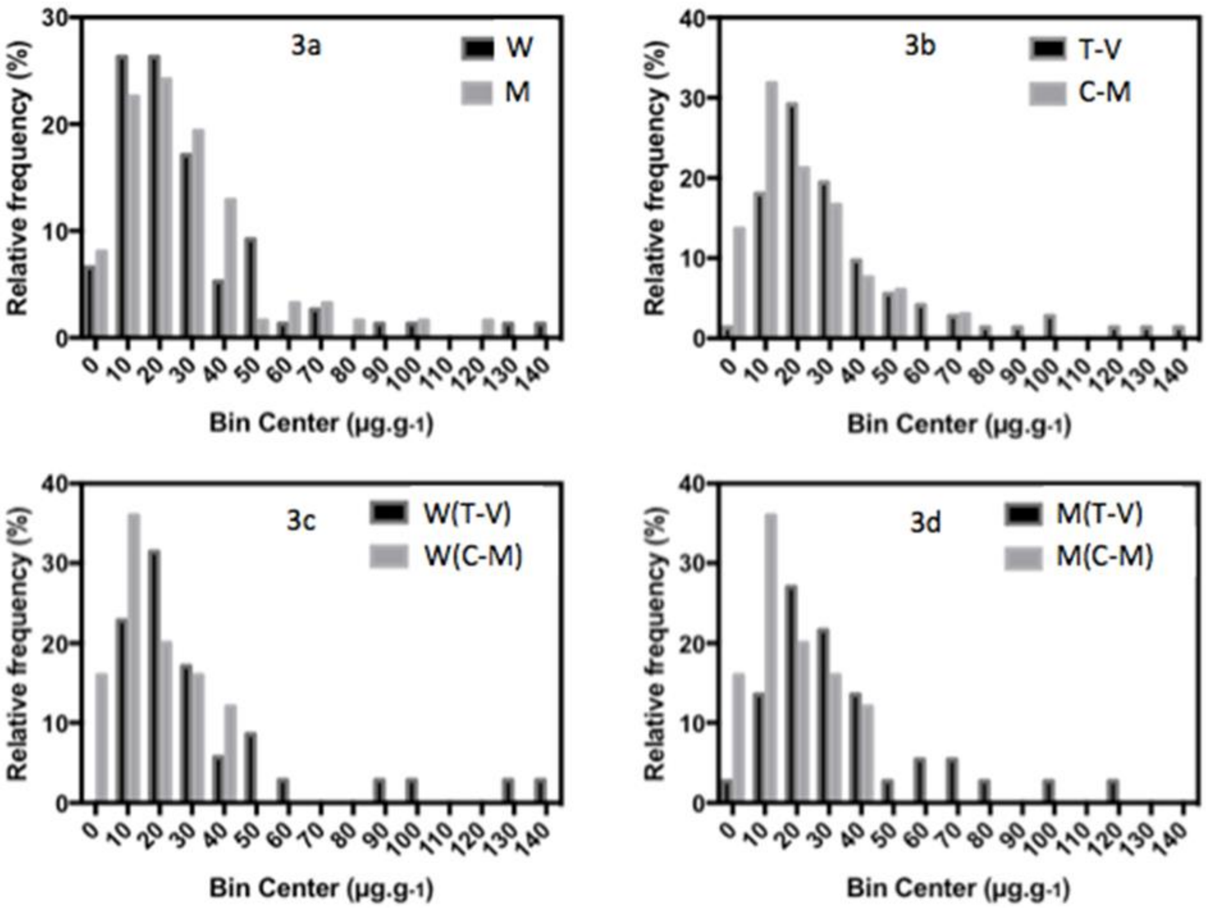


Figure 3: Frequency distributions of hair lead levels in historical samples W: Women; M: Men; T-V: Towns and Valleys; C-M: Countryside and Mountains. Frequency distributions by

gender (3a), by geographic groups (3b), for women by geographic groups (3c), and men by geographic groups (3d).

Figure 3 shows separate histograms describing the frequency distributions of HLL values overall by gender (3a) and by geographical group (3b), and then of women by group (3c) and men by group (3d). All histograms show a non-Gaussian distribution with the majority of data below 50 $\mu g.g^{-1}$ and some values (not outliers) ranging up to around 140 $\mu g.g^{-1}$, for some hair strands sampled in towns or industrial valleys. A comparison of distributions, class by class, with the Mann-Whitney and Kolmogorov-Smirnov t-tests shows significant differences between the T-V and C-M groups for men, between the T-V men and the C-M women, and finally between the T-V women and the C-M men, with p values < 0.05 by both t-tests.

Finally, the main results show that HLLs were: i) high throughout Savoy at the time of hair sampling (1880-1882); ii) significantly higher for people living in towns or in industrial valleys, and; iii) significantly lower for men living in the countryside and the mountain areas, compared with women living in the same areas.

3.4 HLL background

HLL background for this study were assessed from a subset of the countryside and mountain areas data. The most isolated sites (representing 28 samples) were La Rochette, Aiguebelette, Thônes, Les Bauges, and Vallorcine/Chamonix (Figure 2), with a mean value of 12.7±1.6 $\mu g.g^{-1}$. For contemporary data, the HLL background ranges from around 0.45 $\mu g.g^{-1}$ (Varrica et al. 2018) to 2 $\mu g.g^{-1}$ (Furman and Laleli 2000), after the strong decrease around 1990-1995 following the introduction of reduced-lead and unleaded gasoline. During this period, mean HLL values fell from 8.8 to 4.1 $\mu g.g^{-1}$ (Schuhmacher et al. 1996), the latter very close to the HLL background reported by Revich (1994). These observations show that the impact of leaded products (e.g., paints, kitchenware, beverages and cosmetics) might have been as important contamination source around 1870 as that of leaded gasoline at the end of the 20th century.

4 Discussion

Before considering the historical factors of lead contamination and the potential health effects, some questions remain unresolved regarding the study design. In this study, hair strand samples were characterized by the gender and geographic origin, but no information about age and health status, was available. On the other hand, lead exposure has most often been studied in the literature from blood lead levels (BLL), unfortunately not available from our set of historical samples. Some contemporary studies have considered both HLL and BLL but observed no significant relations between the two (Wilhelm et al. 2002; Sanna et al. 2011; Li et al. 2017). However, earlier works using other hair analysis method (Chattopadhyay et al. 1977; Grandjean 1978) showed some statistical associations between hair and blood levels.

Other anthropological researches are based on data acquired from bones, skulls or skeletons analysis (Swanston et al. (2018), Stadlbauer et al. (2007), bones and teeth acting as reservoirs for several minor and “trace” elements that circulate through the body (Simpson et al. (2021). As a result, our study on historical hair samples will give a partial overview of the lead contamination. Moreover, despite the washing procedure used (Verrey et al. (2019), it seems that there is no consensus on an appropriate cleaning method and it is challenging (from an analytical chemistry perspective) to analytically verify whether all the exogenous Pb has been removed and that the cleaning did not partially digest the hair and remove any endogenous Pb.

4.1 Historical factors of lead contamination

The history of Human lead exposure is coupled with those of lead poisoning (Lin-Fu 1992). Lead poisoning was already known in ancient Egypt, the time of the pre-Greeks, the Greeks and the Romans (Nriagu 1983). Periodically mentioned over the centuries, lead exposure in the workplace became a major public health issue during the first Industrial Revolution, which began with the 19th century. In the same time, the regional increase in lead environmental contamination was mostly driven by coal consumption (Arnaud et al., 2004). An important route of lead exposure was the inhalation of particles (Riva et al., 2012) during occupational activities (e.g., smelters, plumbers, and painters) or from polluted environments, close to mines and factories transforming mining products (foundries), or related to paint chips or coal combustion (Xu et al. 2004). During the 19th century, there was also high demand for lead for the construction of houses and buildings and for renovation with lead metal for roofing and plumbing (pipes). White lead or ceruse (lead carbonate) was also added to paints for external and internal walls, carts, and trains. Both the production and application of ceruse were known to be very dangerous for workers by the mid-19th century, although its use was only banned in the first half of the 20th century (Lestel 2002) under pressure from workers (Rainhorn 2010).

Thus, the overall physical forms of lead acting as contamination sources around 1880 were lead ore (being mined in Savoy), lead metal (used for pipes and water cisterns), lead alloys including pewter (cooking utensils and kitchenware, buckets and tanks), and lead salts (carbonate and sulfur) used in paints, cosmetics, and ointments. Thus, although workers were especially concerned, the general population was exposed. The early industrialization and the presence of mines and related activities in the deep and narrow valleys of Savoy (Maurienne, Tarentaise, and Isère) likely contributed to the existence of air pollution and smog a large part of the year. The period of hair sampling here corresponded to the end of railway construction between the main towns (Chambéry, Annecy, Aix les Bains), industrial valleys (Maurienne and Tarentaise) and Italy (Turin). These trains undoubtedly transported ore, metals, and related byproducts from the lead-silver and iron mines in the heart of these valleys (Borrel 1889) towards downstream factories and towns. These global environmental contaminations related to industrial activities seem to explain the higher exposure of urban and valley dwellers (T-V) compared to country and mountain dwellers (C-M).

The exposure resulting from the ingestion of dissolved lead in water, wines, or food was a source of concern. By the end of the 19th century, water distribution networks were strongly developed in cities with public fountains, mostly using lead pipes (Goubert 1986; Troesken 2006), even if lead pipes were already known to be responsible for drinking water poisoning (Pascal, 1870). Water was also collected for domestic use from fountains and transported home in pewter buckets or tankards, and pewter or glazed pottery containing 10 to 50% lead was used for serving beverages. Pewter kitchenware was also common, and contact with food and liquids was known to release dissolved lead. Moreover, ingestion of lead was also likely to result from wine, cider and spirit consumption (Hernberg 2000). Savoy has been known since the Roman period for its dry, acidic wines, with vineyards mainly located near Chambéry and north of Aix les Bains. at the time and until the 20th century, and these wines were often sweetened by adding sugar of lead (lead acetate) or litharge (lead oxide). A part of the production was transformed by home distillers into a local spirit ("marc" of Savoy) using a pot still with a boiler and condenser. The top of the boiler (the "still head") and the condenser (known as a "worm") were made of pewter, usually containing from 10 to 20% lead. This way of contamination was already known with the distillation of rum, early suspected to be responsible for lead poisoning of slaves and colonists in colonial North America (McCord 1953), this hypothesis was reinforced by analysis of slave bones demonstrating lead poisoning of slaves in Barbados in the 17th century (Handler et al. 1986).

Moreover, another source of individual lead exposure conceivably occurred through the inhalation of cigarette smoke. After the invention of the cigarette rolling machine in the 1880s, cigarette smoking was no longer rare, although it did not become frequent until World War I (Proctor, 2004).

Skin absorption was another route of lead exposure (Pascal, 1870). At least from the time of the Roman Empire, women have used cosmetics (color and hair cosmetics, care products for the face and body…) containing toxic metals including lead. Specific metals involved have varied according to geographical areas over the millennia, and these cosmetics remain an important health concern today (Lessler, 1988; Lanoë 2002; Borowska and Brzoska, 2015). The significantly lower average HLL recorded in this study for men in the countryside and the mountains compared with the women living there most likely reflects gender differences in living habits.

4.2 Historical health effects

The life expectancy of women in Savoy at the end of the 19th century was 45 years, and for men 43 years (Meslé and Vallin 1989), due mainly to epidemics, diseases, stillbirths, child mortality, and more globally social precarity. Other causes, such as lead poisoning as indicated above, were nonetheless already known (Orfila 1843). Among the diseases listed in Savoy in the 19th century, goiter and cretinism especially were endemic and known through the popular French expression “crétin des Alpes” (“moron of the Alps”, the mountain range in Savoy). Jules Carret (cited in Billy 1962), the person who most likely collected the hair used here, reported in 1880-1882 that the highest goiter rates — 11% of population — were observed in Maurienne and Tarentaise valleys. It is particularly noteworthy that this high incidence rate was recorded very close to lead mines. Interestingly, the high rate of consanguinity in Savoy valleys, as well as poor hygiene and contaminated drinking water, were first reported to be promoting factors (Billy 1962).

In the XIXth century, saturnism encephalopathy and related diseases were known and described in several illnesses (cited in Lucchini et al. 2012): French physicians (Louis Tanquerel des Planches (1810–1862) and Jean-Etienne Dominique Esquirol (1772–1840)), followed some decades later by the British physician Daniel Hack Tuke (1827–1895) who drew attention in 1880 to cases of mental disorders resulting from chronic ingestion of minute amounts of lead. At the beginnings of the 20th century scientists identify the ingestion of flakes of lead-based paint (due to pica in infants and young children) as well as water supplied through lead pipes as the main causes of chronic environmental poisoning by lead (Lucchini et al., 2012).

Relations between lead exposure and thyroid functioning were confirmed more recently. The association between lead and thyroid disease might involve the depression of thyroid function as a result of intense long-term lead exposure among workers (Tuppurainen et al. 1988). Moreover, FT4 (free thyroxine) levels in blood may be inversely related to long-term lead exposure (Bledsoe et al. 2011). Nontoxic diffuse goiter was also recently found to be associated with high blood lead levels in adolescents, compared with healthy adolescents

(Savchenko and Toupeleev 2012). Similar observations have been made for pregnant women exposed to lead, which contributes to maternal thyroid dysfunction by stimulating thyroid autoimmunity (Kahn et al. 2014). Inverse correlations have been reported between the stature and blood lead levels in the range of 5 to 35 µg/dL for US school children (Schwartz et al. 1986; Cassidy-Bushrow et al. 2016). Very recently, Cai et al. (2021) studied the blood lead level of 255 children living nearby a zinc-lead mine in China. They observed that high lead exposure affects the serum TSH (thyroid stimulating hormone), GABA (gamma-aminobutyric acid) levels and IQ

Thus, the lead contamination revealed in our study might have contributed to the high rates of goiter observed in Savoy during the 19th century. This endemic disease was strongly associated with HLL in the industrial valleys (Maurienne and Tarentaise). In towns where HLL was also high, the rates of goiter and cretinism might logically have been lower than in valleys because of the beginning of prophylactic iodine addition (Gueorguiev, 2010) to salt and water in this period and the lower rate of consanguinity (Billy 1962). While the prophylactic iodine action was suggested by Coindet around 1820 (Dreyfuss 2005), and the stamping-out of goiter program started in the late 1860 (Zimmermann, 2008), several hypotheses were proposed for the explanation of goiter cause, among which those of Adolphe Chatin (1851) who wrote that goiter is a natural disease limited by iodine whose effect could be neutralized by an element present in water.

Jules Carret at the origin of historical hair sampling, stated in 1884 that a microbe living in soil and transported in water was responsible for goiter, but he also considered environmental factors such as soil nature, altitude and exposure of living areas.

Given that exposure to lead can also cause a broad range of very adverse effects (e.g., developmental, hematological, neurological, renal, gastrointestinal, and rheumatological) in humans, it is possible that the health impact of the lead contamination was not restricted to thyroid function.

5 Conclusion

Lead poisoning was already known in Antiquity, but in the 19th century it reached epidemic dimensions during the period of industrialization, and thus was “rediscovered” (Ernberg, 2000). Our analysis of inorganic elements in historical hair samples reveals quite high levels of contamination by lead, in Savoy around 1880, which is one the most common environmental toxic heavy metal (Zhai et al 2015). People living in towns and industrial valleys presented the highest lead contaminations, and, retrospectively, we see that these sites were associated with high rates of goiter during the sampling period. The thyroid's known naturally high affinity for metals, namely lead does not rule out a concomitant lack of dietary iodine. Each factor undoubtedly reinforced the other, especially given the iodine-poor soil of the Alps (Kapil, U. (2007).

In conclusion, this study shows both the feasibility and utility of hair analysis as a biomarker for historical studies of environmental or occupational contamination. It is especially interesting when we consider that knowledge of past exposures of ancient populations offers a powerful bioanthropological tool for understanding the past in its detailed environmental, social, and health contexts (Baez et al. 2000). Moreover, an understanding of the connections between past and present is useful not only for deciphering current exposure situations for humans but also for apprehending how human societies have evolved, how human populations have adapted to their environment, and how some exposures today are related to various health problems.

Credit author statement

Olivier Thomas. Conceptualization, investigation, methodology, statistical analysis, data interpretation, writing and correction; Barbara Le Bot. Methodology, analytical supervision, manuscript correction; Dominique Verrey. Samples handling, analytical design, washing method development; Severine Durand. Analytical design, washing method development, analytical data production; Cyrille Harpet. Samples handling, manuscript revision; Alain Froment. Acess to hair collection, sampling authorization, historical help manuscript correction; Bernard Jégou. Supervision, conceptualization, resources, manuscript writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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