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ARTICLE

# Exposure of adults to extremely low frequency magnetic field in France: results of the EXPERS study

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**Abstract** – Assessing the exposure of adults to magnetic field is a central point in the context of epidemiological studies. The EXPERS study is the first study at national scale in Europe with measurements of personal exposure to extremely low frequency magnetic fields, involving 1046 French adults with 24 h personal measurements. The proportion of adults with a 24 h AM of ≥ 1 μT was 2.1% for all adults and 0.3% for adults for which no alarm clock was identified, as this requirement of the measurement protocol was sometimes not respected. The alarm clocks were the main variable linked to the adults' exposure measurements. The vicinity of the home to a high voltage power line increased the magnetic field exposure. However, only 1.7% of the adults were living close to a 63 to 400 kV overhead line, and only one of them had a personal exposure ≥ 1 μT with an AM of 1.1 μT. The exposure of adults was also correlated with some characteristics of the home and its environment, and some durations of activities, such as the duration of work and the duration in rail transport. The distribution of adults' personal exposure was significantly different from the distribution of exposure during sleep, and from the distribution of exposure assessed from measurements during sleep and work. This highlights the complexity of the exposure assessment in epidemiological studies.

**Keywords:** magnetic field / population exposure / occupational exposure

## 1 Introduction

The assessment of the exposure of subjects is always a crucial point in epidemiological studies. This is also the case for epidemiological studies about potential health effects of electromagnetic fields (EMF). The case of adult subjects is even more complex due to the numerous exposure situations during the day. When characterizing the exposure to extremely low frequency (ELF) magnetic field, most studies have considered separately and only the occupational exposure or the residential exposure. The residential exposure can be assessed by the distance to power lines or the calculation of magnetic field close to power lines. The occupational exposure can be assessed by job exposure matrices. Few studies have considered the global exposure of adults using magnetic field measurements.

The results are not easy to compare due to the diversity of indicators. Some studies have looked to the exposure at home, with some punctual measurements or at a fixed point. Using the arithmetic mean (AM) for each subject, the proportion of subjects exposed at more than 0.2 μT is between 7 and 9% in California and England in the general population (Perry *et al.*, 1981; Wrensch *et al.*, 1999; London *et al.*, 2003), and around 20% for those living close to power lines in Sweden (Feychting and Ahlbom, 1994). To describe measurements of personal exposure, most authors use the AM, but some of them use a percentile (Li *et al.*, 2010), which can be the median (Li *et al.*, 2011), or the number of measurements above a threshold (Savitz *et al.*, 2006). The biggest published exposure data come from a German study in Bavaria, where 1952 subjects have worn a EMF meter during 24 h. These subjects were recruited after an article in local newspapers, and quotas were fixed to represent the geographical distribution of the population (Brix *et al.*, 2001). For all Bavarian subjects, the AM of the 24 h AM was 0.101 μT. This mean exposure was a little higher for subjects living close to power lines (0.112 μT), but also for subjects working (0.153 μT) and for subjects sleeping close to electric alarm clocks (0.149 μT). The mean exposure was also a little higher in winter (0.103 μT) than in summer (0.099 μT). In the Netherlands, 99 measurements of 24 h on subjects recruited in an internet panel with quotas on demographic characteristics resulted in an AM of 24 h AM exposure of 0.132 μT (Bolte *et al.*, 2015).

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The proportion of subjects exposed to 0.2 μT and more is 13.6% in 3 cities of north California (Mezei *et al.*, 2001) and 44.1% for those living close to power lines in Sweden (Forssen *et al.*, 2002). In a big exposure study over the USA, 1012 measurements of 24 h were recorded (with 874 subjects of age 18 years and more) and the mean exposure was 0.125 μT (Zaffanella and Kalton, 1998).

The previously published exposure data about adults in France were limited to spot measurements in the department of Côte d'Or in 153 homes representative of homes within this department. The median of measurements was 0.011 μT and the 95th percentile was 0.121 μT. The exposure was thus lower than in the literature but this region of France is mainly rural and not representative of more urbanised areas.

The Ministry of Solidarities and Health initiated a study on the exposure of the French population to 50 Hz magnetic fields with the objective to quantify this exposure and to its sources. This study, named EXPERS (EXPosition PERSonnelle in French), is composed of a sample of children (0–14 years old) and a sample of adults (≥ 15 years old) located throughout the country. The results for children were previously published (Magne *et al.*, 2017) and we present here the main results for the adults.

## 2 Materials / subjects and methods

The main points of the protocol (Bedja *et al.*, 2010) are summarized below.

### 2.1 Recruitment of the subjects

The subjects were recruited randomly on the French phone lists, using a quota over the 22 French regions. The objective was to have a sample size of 1000 adults in order to have the same size than for children. The measurements were planned during cold seasons (February–April 2007, October 2007–April 2008 and October 2008–January 2009) because the exposure to ELF magnetic fields is supposed to be higher due to higher electric consumption. Because of difficulties for children recruitments, we authorized finally the recruitment of one child and one adult of the same family (Magne *et al.*, 2017). As described below, this has introduced some bias in the sex ratio and age distribution for adults.

### 2.2 Measurement protocol

Each adult wore an EMDEX II (Enertech, USA) over 24 h during a usual working day. The meter was set to measure broadband (40–800 Hz) and harmonics (100–800 Hz) magnetic fields every 3 s. During the night, the EMDEX was supposed to be put at a distance of > 50 cm to any electric appliance (especially electric alarm clock). This distance of 50 cm ensures to measure the personal exposure during the sleep and not the magnetic field emitted by electric appliances which is not representative of the exposure of the person when the measurement point is located very close to these devices.

### 2.3 Collection of data

A pollster gave the EMDEX to the adult and filled in a questionnaire about the subject and their home. The adult filled in a timetable, detailing his/her activities during the measurement period. The French grid operators (RTE for high voltage, and Enedis for medium voltage (MV, mainly 20 kV) and low voltage (LV, 400 V)) identified electric networks close to the home or the workplace from the addresses converted into Lambert II coordinates. The criteria of vicinity between an address and an electric network were to be at a distance ≤ 200 m for 400 kV overhead lines, 120 m for 225 kV overhead lines, 100 m for 150 kV overhead lines, 70 m for 63 or 90 kV overhead lines, 20 m for 63 to 225 kV underground cables and 40 m for all MV and LV lines and cables and for MV/LV substations.

### 2.4 Validation of the database

The duration of activity and different metrics (including arithmetic mean (AM), geometric mean (GM), median and maximum) have been calculated for 14 predefined types of activity:
- 24 h exposure;
- at home;
- sleep;
- at home excluding sleep;
- at home using TV, PC or video games;
- at work;
- at work in a building;
- at work outside;
- at work using PC;
- at work in a car;
- on a train or metro;
- in a car or a bus;
- cycling or walking (in a street, a forest, etc.);
- other activities (for example shopping, visiting a friend, going to the doctor, etc.).

Working at home was not considered as a work period, but as a home period.

The database was validated by control of coherence and finally includes 1046 adults.

### 2.5 Statistical analyses

The software SAS version 9.3 (Cary, NC, USA) was used for the statistical analyses. A standard significance level of 5% has been chosen. All tests are two sided. The tests used are the same as in Magne *et al.* (2017).

We defined the highest exposure for adults as a 24 h AM ≥ 1 μT. This value of 1 μT comes from an instruction about urbanism close to power lines which recommends to not build new sensitive buildings in area exposed to a magnetic field higher than 1 μT (Ministre de l'écologie du développement durable et de l'énergie, 2013).

## 3 Results and discussion

### 3.1 Descriptive results

All magnetic field measurements are expressed here in broadband (40–800 Hz) excepted where other components are mentioned.

**Table 1.** Distribution of ages in EXPERS study compared to the French population.

| Age (Years) | EXPERS (%) | France (%) |
|---|---|---|
| 15–24 | 6.5 | 15.5 |
| 25–34 | 16.0 | 15.5 |
| 35–44 | 39.4 | 17.3 |
| 45–54 | 19.9 | 16.7 |
| 55–64 | 8.9 | 14.7 |
| 65–74 | 5.7 | 9.8 |
| 75–84 | 3.4 | 8.3 |
| > 84 | 0.2 | 2.2 |

**Table 2.** Distribution of urban environments in EXPERS study compared to the French population (commune belonging to an urban area of).

| | EXPERS (%) | France (%) |
|---|---|---|
| Rural | 21.5 | 22.1 |
| 2000–4999 inhabitants | 6.4 | 6.6 |
| 5000–9999 inhabitants | 7.0 | 5.7 |
| 10 000–19 999 inhabitants | 4.6 | 4.9 |
| 20 000–49 999 inhabitants | 5.2 | 6.6 |
| 50 000–99 999 inhabitants | 6.3 | 7.3 |
| 100 000–199 999 inhabitants | 5.4 | 6.5 |
| 200 000–1 999 999 inhabitants | 27.5 | 24.2 |
| Paris | 16.2 | 16.2 |

First, we compared the EXPERS database with the general French population of adults. The data for the general French population came from the 2008 census by the National Institute for Statistics and Economic Studies (INSEE, Paris, France). As expected from the quota definition by region, the repartition of the adults in the sample is not statistically different from the French adults repartition over the 22 regions ($P = 1$). The adults in the EXPERS database were 373 men (35.7%) and 673 women (64.3%). We explain this important difference by the fact than when a child and an adult of the same family participate to the study, the adult was most of the time the mother.

Adults of 35–44 years are overrepresented compared with the general French population ($P < 0.001$) (Tab. 1). The 15–24 and more than 54 year-old adults are underrepresented. This is linked to the overrepresentation of mothers of 0–14 year children in our adult sample.

All types of urban environments are represented in the sample. Around one over five (19%) live in Ile-de-France (Paris region). The distribution of adults in function of the size of the urban unit of the commune of residence is representative of the French population ($P = 0.0743$; Tab. 2). The urban unit is defined by INSEE as a group of communes in which the distance between buildings is $\leq 200$ m.

The distribution of adults in function of socio-professional categories is not representative of the French population

**Table 3.** Distribution of socio professional categories in EXPERS study compared to the French population.

| | EXPERS (%) | France (%) |
|---|---|---|
| Self-employed farmer | 1.4 | 1.0 |
| Craftsmen, shopkeepers, company managers | 3.3 | 3.3 |
| Middle managers and higher intellectual professions | 16.3 | 8.7 |
| Intermediate professions | 30.1 | 13.0 |
| Employees | 21.4 | 16.4 |
| Workmen including farm workers | 5.8 | 13.1 |
| Other without professional activity and inactive having already worked | 21.6 | 44.5 |

(Tab. 3). Intermediate professions are overrepresented compared to people without professional activity and inactive people having already worked ($P < 0.001$). This is also linked to the recruitment of adult and child of the same family.

In EXPERS study, 69.8% of the adults are living in houses (18.4% in terraced houses and 51.4% in single houses) and 30.2% in apartments (8.2% in a building with 2 to 9 apartments and 22% in a building with $\geq 10$ apartments).

On average, the families are composed of two adults and one child. The adults have spent 10.5 years in this home. There is a wide dispersion in the year the homes were built: 25.9% before 1950, 16.2% between 1950 and 1969, 27.1% between 1970 and 1989, and 25.4% after 1990 (data are missing for 5.4%).

Most of the homes have individual heating (84.9% *versus* 15.1% collective) and individual water heating (90% *versus* 10% collective). The type of energy heating is electric for 235 adults (22.5%), which is a little less than in France (25.7% for main homes). The type of energy heating is non-electric for 635 adults (60.7%), mixed for 151 adults (14.4%) and unknown for 25 adults. Heating equipment without emission of a high magnetic field is used in 94.3% of adults' homes, whereas 5.7% have at least one equipment emitting a high magnetic field: 21 homes with accumulation heating, 17 with electric blankets and 22 with electric underfloor heating. The type of energy used for water heating is electric for 388 adults, non-electric for 372 adults and unknown for 286 adults.

The subjects had been asked to not to put the EMDEX at a distance of $< 50$ cm from an electrical appliance during the night. However, 103 adults wrote in the questionnaire that they did not respect this instruction. This instruction has been respected by 629 adults, but this item is unknown for 314 adults. An alarm clock was identified on the measurement curves during the night for 15.2% of the adults.

Over the 24 h measurement period, the adults stayed 17.4 h at home, including 8.4 h of sleep (Tab. 4). We defined as "work" the location where the adults spent most of their time outside the home: depending on their age, adults are at school, university or at their workplace. Six hundred and twelve adults (58.5%) went to work, and 47.7% of them used PC at work for 6 h on average. Three quarters of the adults (76.7%) used car or

**Table 4.** Duration of different activities of adults during the 24 h measurement period.

| | Number of adults (% of $N$) | AM of duration in h (standard deviation) | Median of duration in h |
|---|---|---|---|
| All adults ($N$ = 1046) | | | |
| 24 h | 1046 (100%) | 24.6 ± 0.8 | 24.4 |
| At home | 1046 (100%) | 17.4 ± 4.1 | 16.6 |
| Sleep | 1041 (99.5%) | 8.4 ± 1.4 | 8.5 |
| At home excluding sleep | 1046 (100%) | 9.1 ± 3.9 | 8.3 |
| At home using TV, PC, etc.. | 888 (84.9%) | 3.9 ± 2.7 | 3.3 |
| On a train or metro | 58 (5.5%) | 1.7 ± 1.2 | 1.4 |
| In a car or a bus | 802 (76.7%) | 1.7 ± 1.5 | 1.3 |
| Cycling or walking | 374 (35.8%) | 1.3 ± 1.3 | 1.0 |
| Other activities | 590 (56.4%) | 1.9 ± 1.7 | 1.5 |
| Adults working[a] outside the home $N$ = 612 | | | |
| At work | 612 (100%) | 7.6 ± 2.5 | 7.9 |
| At work in a building | 591 (96.6%) | 7.2 ± 2.6 | 7.8 |
| At work using PC | 292 (47.7%) | 6.0 ± 2.7 | 7.0 |
| At work in a vehicle | 46 (7.5%) | 4.8 ± 3.1 | 3.6 |
| At work outside | 32 (5.2%) | 3.8 ± 2.9 | 2.8 |

[a] Work = the location where the adults spent most of their time outside the home, depending on their age (ex school, university, work).

**Table 5.** Electric networks in the vicinity of homes and schools of subjects from geolocalisation of the address.

| Type of network (distance of search around) | Home ($N$ = 1046) Number of adults (% of $N$) | Work* ($N$ = 612) Number of adults (% of $N$*) |
|---|---|---|
| LV underground cable (40 m) | 686 (65.6%) | 347 (66.1%) |
| LV overhead line (40 m) | 466 (44.6%) | 166 (31.4%) |
| MV underground cable (40 m) | 427 (40.8%) | 301 (57.2%) |
| MV overhead line (40 m) | 43 (4.1%) | 12 (2.3%) |
| MV/LV substation (40 m) | 160 (15.3%) | 110 (20.8%) |
| MV/LV substation inside building (40 m) | 59 (5.6%) | 44 (8.3%) |
| MV/LV substation inside building possibly adjacent to the address | 36 (3.4%) | 20 (3.8%) |
| MV/LV substation inside building possibly adjacent to the address and the floor | 11 (1.0%) | Not applicable |
| 225 kV (120 m) or 400 kV (200 m) overhead line | 8 (0.8%) | 6 (1.1%) |
| 63 or 90 kV (70 m) or 150 kV (100 m) overhead line | 10 (1.0%) | 4 (0.8%) |
| 63 to 225 kV underground cable (20 m) | 7 (0.7%) | 7 (1.3%) |
| Influence of electric network identified on magnetic field curves | 130 (12.4%) | – |
| If 63 to 400 kV lines or cables close to home, magnetic field proportional to the current in the line/cable | 25 (2.4%) 14 (1.3%) | 17 (3.2%) 2 (0.4%) |

* % calculated excluding 87 missing data of work location.

bus for 1.7 h on average. Only one third of the adults (35.8%) walked or cycled for 1.3 h on average. More than half of the adults (56.3%) had another activity for 1.9 h on average.

There are very few adults living close to 63 to 400 kV lines (Tab. 5): only 0.8% live at < 125 m to a 225 kV line or < 200 m to a 400 kV overhead line and 1.1% go to work with the same criteria distance to those lines.

The distribution of AM over 24 h is given in Figure 1 (see Supplementary Data 1 for GM and median).

The mean 24 h AM is 0.14 µT (Tab. 6), which is higher than for children (Magne *et al.*, 2017). This is a little more than 0.101 µT in the Bavarian study, which is the single comparable study (Brix *et al.*, 2001), but comparable to the working people or people close to electric alarm clock. Without electric alarm clock, the mean 24 h AM decreases to 0.07 µT for the adults (Tab. 8).

### 3.2 The highest exposures

There are 22 adults in the highest exposure class (24 h AM ≥ 1 µT). These highest exposures are caused by the close proximity of an alarm clock (19 adults), the presence close to

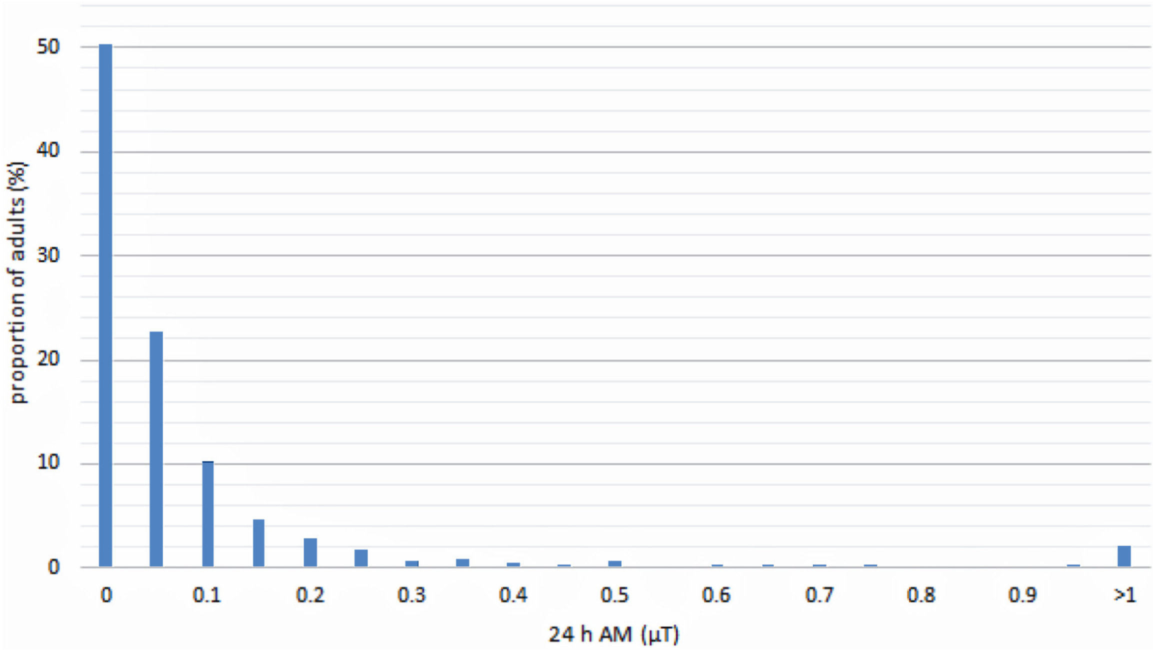


**Fig. 1.** Distribution of 24 h AM among adults.

**Table 6.** Main results for ELF magnetic field exposure over 24 h.

| | Arithmetic mean 24 h (µT) | Geometric mean 24 h (µT) | Median 24 h (µT) |
|---|---|---|---|
| Indicators | | | |
| AM (standard deviation) | 0.14 (0.46) | 0.04 (0.07) | 0.04 (0.12) |
| 25th Percentile | 0.03 | 0.01 | 0.01 |
| Median | 0.05 | 0.02 | 0.02 |
| 75th Percentile | 0.11 | 0.04 | 0.05 |
| 90th Percentile | 0.23 | 0.08 | 0.09 |
| Max | 7.46 | 1.16 | 2.63 |

the home of 90 kV overhead line (1 adult) or the use of 50 Hz electrified train with instantaneous values higher than 100 µT (1 adult), a source at work for a teacher (1 adult), the proximity to different sources in a kitchen from which one is a microwave oven and another is perhaps an electric oven (1 adult). The 50 Hz electrified train with instantaneous values higher than 100 µT was in used at the time of the measurement but is not used anymore today. One adult has 2 sources, and for 3 adults the source is not an alarm clock but another of the above listed sources. If we exclude the adults for which an alarm clock is identified during the night, as these alarm clocks are a mistake in the measurement, because the protocol was not respected, the proportion of adults with an AM ≥ 1 µT would be 0.3% and the mean value during sleep would be 0.04 µT which is in line with Bavaria where mean exposure during the night without electric alarm clock is 0.058 µT (Brix *et al.*, 2001).

None of these 22 adults were close to a 225 or 400 kV line, and only one was close to a 90 kV line. Excluding those for which the main source was an alarm clock, the 8 adults living close to a 225 or 400 kV overhead line had a 24 h AM < 0.8 µT, and the 10 adults living close to a 63 to 150 kV overhead line had a 24 h AM < 1.1 µT.

We also tried to characterize the 24 h AM in order to look for variables associated with exposures of ≥ 1 µT. The same variables were crossed-referenced with this dichotomous variable. A few of them appear to be significantly correlated. In order to assess the relative weight of each variable, a multivariate logistic regression tested these variables and those significant at a level ≤ 20%, but the model did not converge, probably because of the small number of subjects in this highest exposed class. However, as the main source of exposure was found to be the alarm clock in this group, and in order to follow the same analysis as for the children, we decided to exclude from our analysis adults with an alarm clock identified on magnetic field measurements during the night in order to be able to see whether other variables have an influence on the magnetic field exposure level.

The 24 h AM is quite dependant of high punctual magnetic field values, for example values > 100 µT. Magnetic field values of > 100 µT at 50 Hz were measured for 16 adults (0.01%). We speak here about 50 Hz component and not broadband component because ICNIRP reference levels decrease between 100 µT at 50 Hz and 6.25 µT at 800 Hz. The exposure sources are mainly in residential environment (7 anti-theft devices in shops, 2 suburban trains powered at 50 Hz which are not used anymore today, 2 electric appliance in the kitchen). Some sources can be found in occupational environment (1 work with tractor, 1 jackhammer, 1 work on generator in a hospital, 1 teacher in a high school). The last one was measurement error (using of the verification source for the EMDEX recorded). The time passed over 100 µT is less than 1 minute for all adults, excepted 2 min and 15 seconds for the electric appliance in the kitchen. Most of the time, it lasts only

**Table 7.** Variables correlated with at least one of the following indicators over 24 h: arithmetic mean, geometric mean or median.

| | Number of adults | p-value [a] | | |
|---|---|---|---|---|
| | | 24 h AM | 24 h GM | 24 h median |
| Sex | 887 | 0.932 | 0.814 | 0.5145 |
| Age (15–34, 35–44, 45–54, ≥ 55 years) | 887 | 0.8922 | 0.1695 | 0.2307 |
| Duration sleep at home [b] | 882 | 0.1450 | 0.4001 | 0.8611 |
| Duration at home excluding sleep [b] | 887 | 0.0012 | 0.1120 | 0.1107 |
| Duration at work [b] | 513 | 0.0421 | 0.0142 | 0.0248 |
| Duration at work inside building [b] | 495 | 0.0211 | 0.0034 | 0.0076 |
| Duration at work using PC [b] | 238 | 0.4846 | 0.2995 | 0.2565 |
| Duration at work inside vehicle [b] | 36 | 0.4829 | 0.3081 | 0.7808 |
| Duration at work outside [b] | 31 | 0.9740 | 0.7782 | 0.6187 |
| Duration on train or metro [b] | 52 | <.0001 | <.0001 | <.0001 |
| Duration on car or bus [b] | 679 | 0.2432 | 0.0004 | 0.0051 |
| Job (at the time of measurement) | 887 | 0.8298 | 0.0575 | 0.0810 |
| Living in Ile de France | 887 | < 0.0001 | < 0.0001 | < 0.0001 |
| Urban area size (< 5000, 5000–49 999 and > 50 000 inhabitants) | 887 | < 0.0001 | < 0.0001 | < 0.0001 |
| Type of home (house/apartment) | 887 | < 0.0001 | < 0.0001 | < 0.0001 |
| Year home was built (in classes) | 846 | 0.0015 | < 0.0001 | < 0.0001 |
| Type of home heating (individual/collective) | 887 | < 0.0001 | < 0.0001 | < 0.0001 |
| Energy for home heating (electric/non-electric/mixed) | 887 | 0.0219 | 0.0011 | 0.0073 |
| Type of water heating (individual/collective) | 887 | 0.0004 | < 0.0001 | < 0.0001 |
| Electric appliance at less than 50 cm during the night | 887 | 0.0503 | 0.1394 | 0.0294 |
| LV underground cable close to home | 887 | < 0.0001 | < 0.0001 | < 0.0001 |
| LV overhead line close to home | 887 | 0.0084 | 0.0007 | 0.0143 |
| MV underground cable close to home | 887 | < 0.0001 | < 0.0001 | < 0.0001 |
| MV overhead line close to home | 887 | 0.2287 | 0.0372 | 0.0645 |
| MV/LV substation close to home | 887 | 0.006 | 0.0001 | 0.001 |
| MV/LV substation in building close to home | 887 | 0.0079 | < 0.0001 | < 0.0001 |
| MV/LV substation in building adjacent to address of home | 887 | 0.1494 | 0.001 | 0.0044 |
| MV/LV substation in building adjacent to home | 887 | 0.5469 | 0.0581 | 0.1023 |
| 63 to 400 kV overhead line close to home | 887 | < 0.0001 | < 0.0001 | < 0.0001 |
| Electric network identified on measurements at home | 887 | < 0.0001 | < 0.0001 | < 0.0001 |
| LV underground cable close to work | 513 | < 0.0001 | < 0.0001 | < 0.0001 |
| MV underground cable close to work | 513 | < 0.0001 | < 0.0001 | < 0.0001 |
| MV/LV substation in building close to work | 513 | 0.0178 | 0.0103 | 0.0148 |
| MV/LV substation in building adjacent to address of work | 513 | 0.2181 | 0.0437 | 0.0362 |

[a] Spearman's test for quantitative variables; Mann–Whitney (if two categories) or Kruskal–Wallis test (if more than two categories) for qualitative variables.
[b] Quantitative variables.

a few seconds. A one-minute duration represents only 0.07% of the time of a 24 h measurement.

## 3.3 The variables correlated with the exposure

The following results are given for the 887 adults for whom no alarm clock was identified on the magnetic field measurements during the night. The results for all adults ($N = 1046$) are given in Supplementary Data 2.

The variables correlated with the 24 h indicators are presented in Table 7. This correlation does not indicate the type of relationship (*e.g.*, linear) or the sense of variation (*e.g.*, the indicator increases with the variable). More information is given by boxplots in Figures 2–7. Other boxplots are given in Supplementary Data 3. There are differences for six variables between the three exposure indicators (AM, GM and median). This means that these indicators do not characterise the exposure in the same way and it is useful to look at all of them. The 24 h exposure is not correlated with age nor sex. It is also not correlated with the duration of sleep. The duration at home outside sleep is only correlated with AM, with no clear sense of variation. The duration of work is correlated with 24 h exposure, and increases the AM (Fig. 2). The duration in rail transport is correlated with 24 h exposure, and increases the AM (Fig. 3). The duration in car or bus is correlated with GM

**Table 8.** Distribution of adult exposure using different surrogates.

| | Number of adults | AM (SD) μT | 25th percentile (μT) | Median (μT) | 75th percentile (μT) | Max (μT) |
|---|---|---|---|---|---|---|
| 24 h AM | 887 | 0.07 (0.13) | 0.02 | 0.04 | 0.08 | 2.69 |
| Sleep AM | 882 | 0.04 (0.08) | 0 | 0.02 | 0.05 | 1.44 |
| TWA | 882 | 0.06 (0.23) | 0.01 | 0.03 | 0.06 | 6.36 |

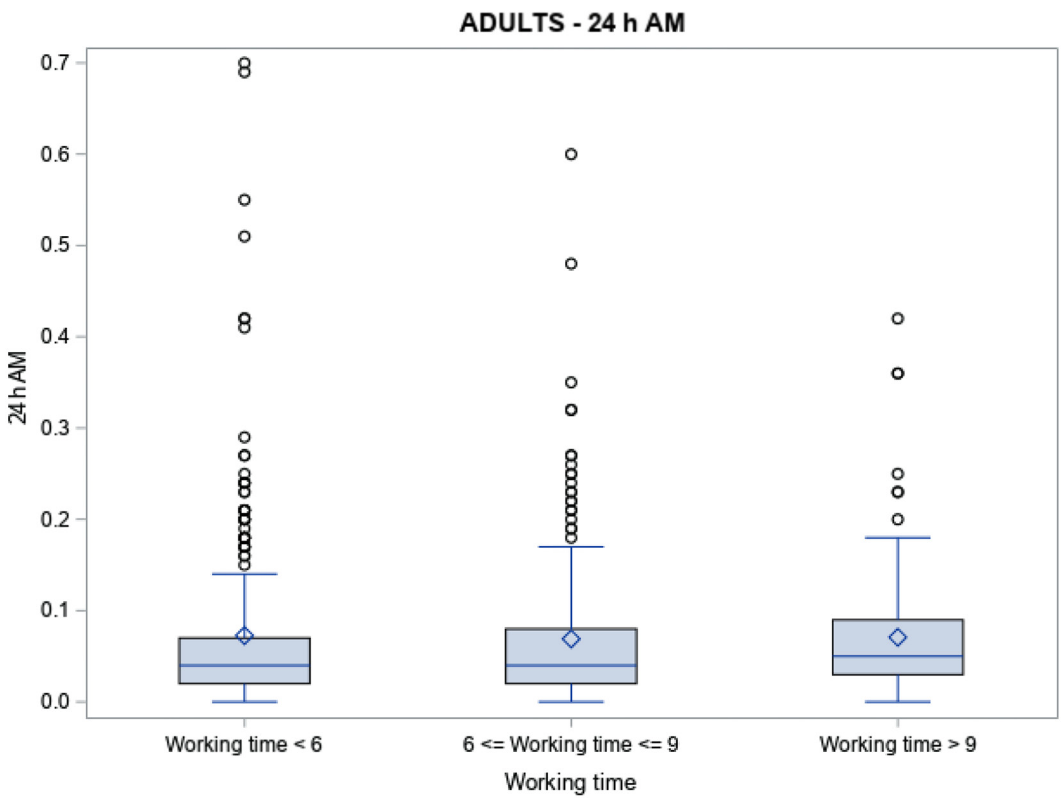


**Fig. 2.** Distribution of 24 h AM in function of working duration.

and median, but not with AM. We distinguished the socio professional categories and the occupation at the time of measurements because some adults were at home for health reasons (such as pregnant women or young mothers). Occupation at the time of measurement was not correlated with the 24 h exposure. The 24 h AM is higher in Ile de France region or in area with highest number of inhabitants (Fig. 4). The 24 h exposure is correlated with the type of home. The sense of variation is not very clear. The AM is lower for detached home. The year the home was built is correlated with the 24 h exposure but the sense of variation is not the same as for the children and there is no clear decrease for the more recent homes. The 24 h exposure is correlated with the heating. The AM is higher for collective heating than for individual heating. The AM is correlated with the type of energy, without any clear relation (Fig. 5). The 24 h exposure is correlated with the presence close to home of LV or MV overhead or underground lines, excepted for MV overhead line where only the GM is correlated. The AM increases with the number of LV or MV underground cable (Fig. 6), but the relation with the number of overhead LV line is not clear. The AM is increased if there is a MV/LV substation inside building close to home (Fig. 7), but there is no correlation if the number of floor or the exact address of the post is taken into account, so this increase is not due to the substation itself. The AM is more clearly increased close to a 225 or 400 kV overhead line (Fig. 8).

### 3.4 Relevance of the exposure indicator

The exposure of the room is often considered as representative of the exposure of the subject when looking at residential exposure. That is why we have compared in Table 8 the distributions of 24 h AM, AM during sleep and TWA (time-weighted average). TWA is defined here *a posteriori* as:

- TWA = 1/3 AM at work + 2/3 AM during sleep for adults going to work;
- TWA=AM during sleep for adults not going to work.

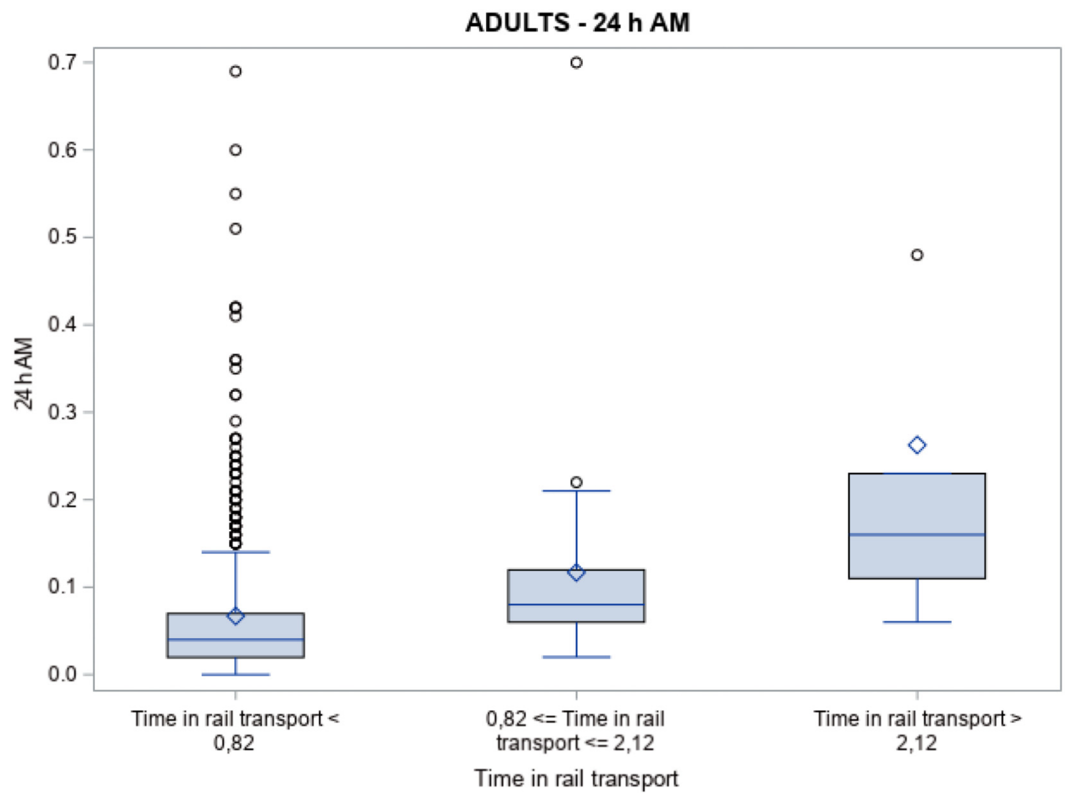


**Fig. 3.** Distribution of 24 h AM in function of duration in rail transport.

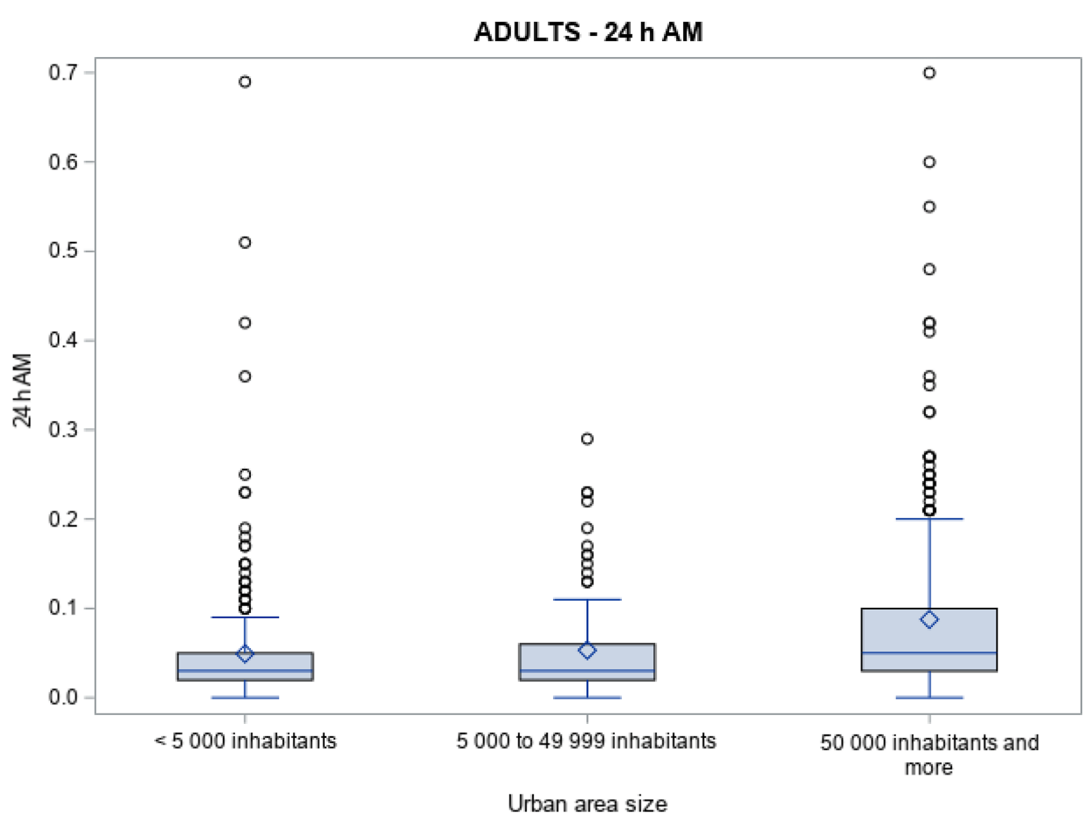


**Fig. 4.** Distribution of 24 h AM in function of urban area size.

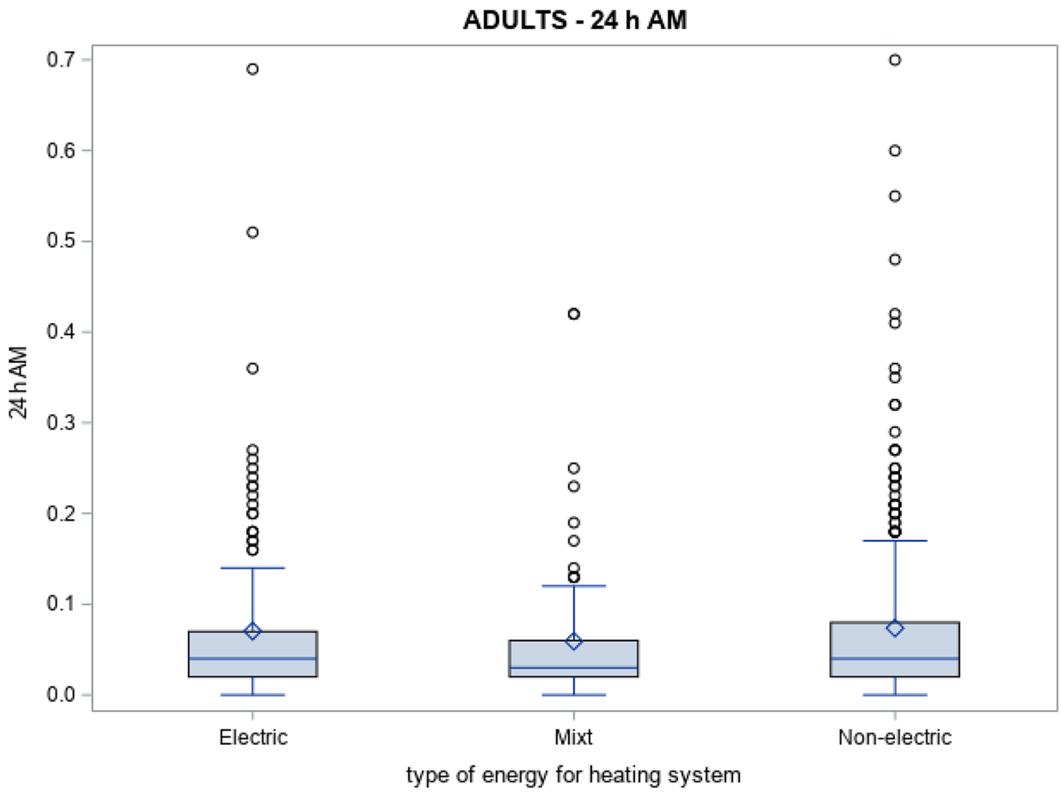


**Fig. 5.** Distribution of 24 h AM in function of type of energy for heating system.

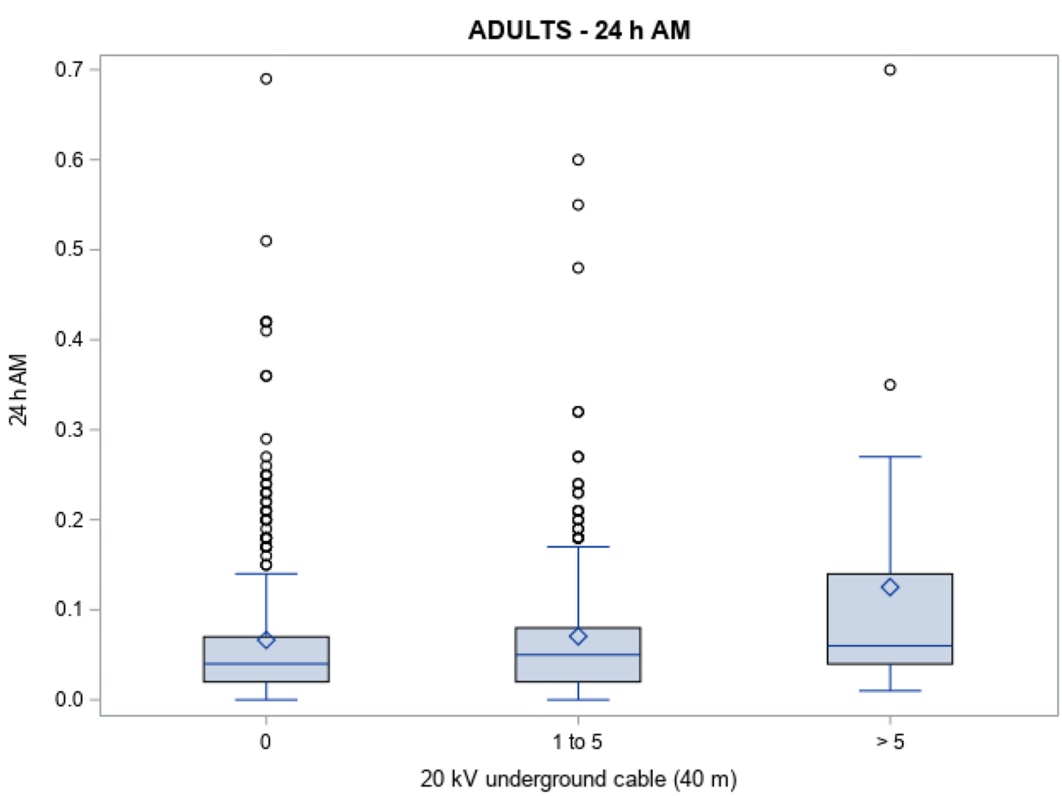


**Fig. 6.** Distribution of 24 h AM in function of number of MV underground cable close to home.

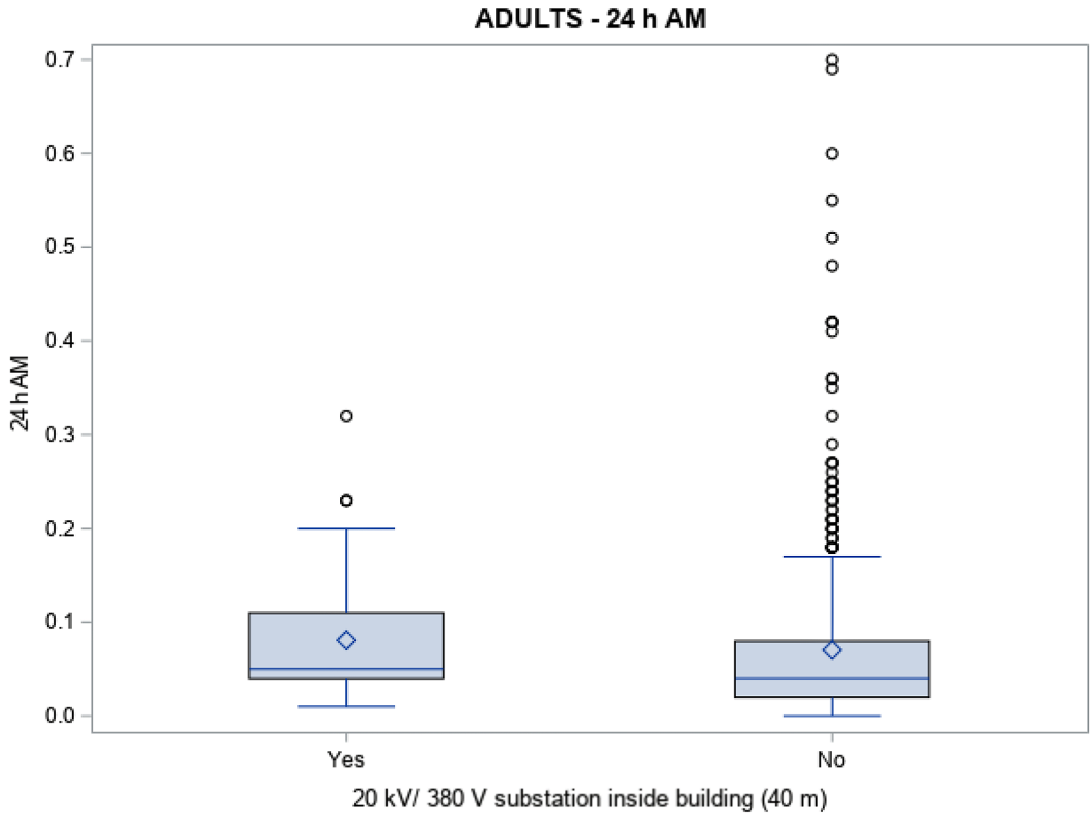


**Fig. 7.** Distribution of 24 h AM in function of LV/MV substation inside building close to home.

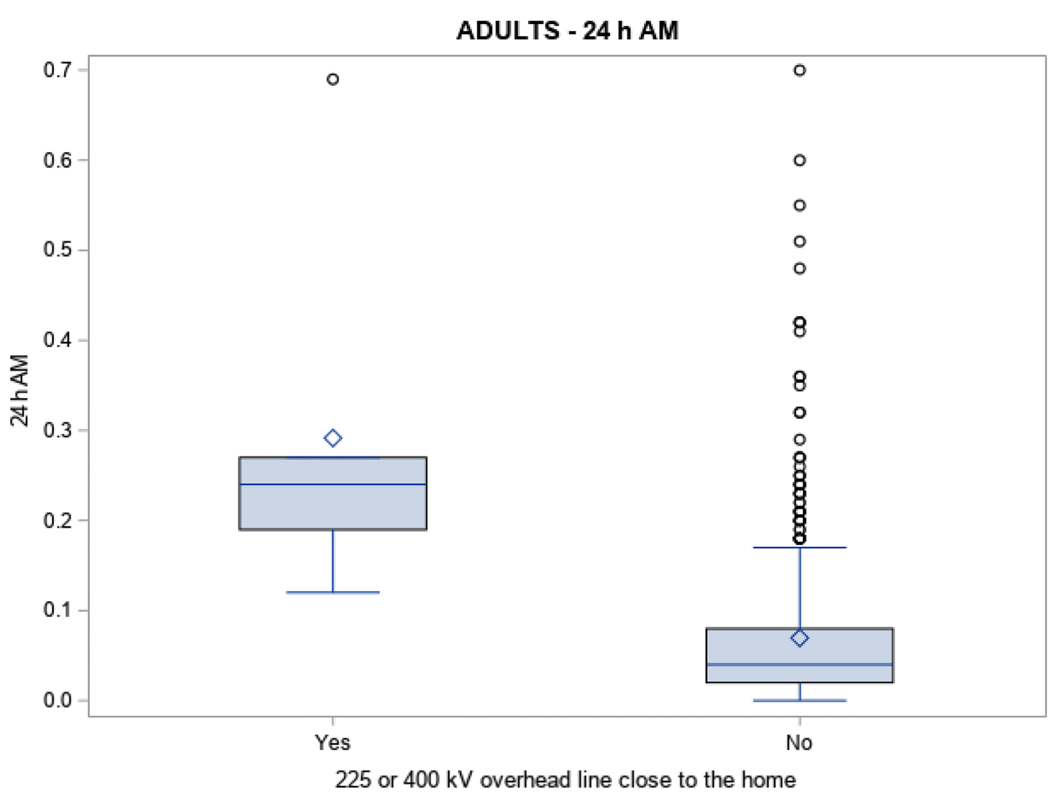


**Fig. 8.** Distribution of 24 h AM in function of 225 or 400 kV overhead line close to home.

The distribution of 24 h AM is significantly different from the distribution of AM during sleep ($P < 0.0001$), and also significantly different from the distribution of TWA ($P < 0.0001$). AM during sleep and TWA are also significantly different ($P < 0.0001$).

Moreover, the numbers of adults with an AM ≥ 1 μT differ: 3 for 24 h AM, 1 for AM during sleep and 2 for TWA.

This result indicates that at the scale of a country, magnetic field measurements at home are not representative of personal exposure of adults. Simplified exposure assessment using measurements at home and at work are also not representative of personal exposure of adults. It is not easy to find an estimator of personal exposure which would be easier to measure. This raises a question regarding the exposure assessment in epidemiological studies, as most of them do not use personal exposure when assessing the exposure of adults.

## 4 Conclusion

The EXPERS study is the first study of magnetic field personal exposure of adults, with a significant number of adults, at the scale of a country in Europe. It is also the first study on this subject in France. We looked for a relationship between the subjects' characteristics and their exposure, and found differences depending on the indicator chosen (AM, GM or median). We studied the AM in more detail and found a correlation between the highest exposures and alarm clocks because of non-respect of the measurement protocol. That is why we performed two analyses, one over all the adults, and one over the adults for which no alarm clock was identified on the magnetic field measurements during the night. The proportion of adults with an AM ≥ 1 μT was 2.1% when considering all adults and 0.3% when excluding those with alarm clocks.

The magnetic field exposure was found to be correlated and increased when the home was located in the vicinity to a 63 to 400 kV overhead line. However, only 1.7% of the adults were living close to these lines, and only one of them had a personal exposure > 1 μT with an AM of 1.1 μT.

The 24 h personal exposure (AM, GM and median) is correlated with some characteristics of the home and its environment, such as the urban area size, the type of home or the type of heating. It is also correlated and increased with the duration of some activities such as the work outside the home (57.8% of the adults) and the transport in train or metro (5.9% of the adults).

The distribution of the 24 h AM, which is the personal exposure of adult, was found to be significantly different from the distribution of the AM during the sleep of adults, or of the TWA that was calculated from AM during sleep and work periods. This highlights the complexity of the exposure assessment in epidemiological studies.

## Supplementary Material

**Supplementary Data 1.** The distribution of 24 h GM and 24 h median for the 1046 adults.

**Supplementary Data 2.** Variables correlated with at least one of the following indicators on 24 h: AM, GM or median, for the 1046 adults.

**Supplementary Data 3.** The boxplots for the variables significantly correlated with the 24 h AM for the 887 adults.

The Supplementary Material is available at https://www.radioprotection.org/10.1051/radiopro/2019032/olm.

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