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Exploring RF-EMF levels in Swiss microenvironments: An evaluation of environmental and auto-induced downlink and uplink exposure in the era of 5G

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ABSTRACT

The advancement of cellular networks requires updating measurement protocols to better study radiofrequency electromagnetic field (RF-EMF) exposure emitted from devices and base stations. This paper aims to present a novel activity-based microenvironmental survey protocol to measure environmental, auto-induced downlink (DL), and uplink (UL) RF-EMF exposure in the era of 5G. We present results when applying the protocol in Switzerland.

Five study areas with different degrees of urbanization were selected, in which microenvironments were defined to assess RF-EMF exposure in the population. Three scenarios of data transmission were performed using a user equipment in flight mode (non-user), inducing DL traffic (max DL), or UL traffic (max UL). The exposimeter ExpoM-RF 4, continuously measuring 35 frequency bands ranging from broadcasting to Wi-Fi sources, was carried in a backpack and placed 30 cm apart from the user equipment.

The highest median RF-EMF levels during the non-user scenario were measured in an urban business area (1.02 mW/m^2). Here, DL and broadcasting bands contributed the most to total RF-EMF levels. Compared to the non-user scenario, exposure levels increased substantially during max DL due to the 5G band at 3.5 GHz with 50% of the median levels between 3.20 and 12.13 mW/m^2, mostly in urban areas. Note that the time-division nature of this band prevents distinguishing between exposure contribution from DL beamforming or UL signals emitted at this frequency. The highest levels were measured during max UL, especially in rural microenvironments, with 50% of the median levels between 12.08 and 37.50 mW/m^2. Mobile UL 2.1 GHz band was the primary contributor to exposure during this scenario.

The protocol was successfully applied in Switzerland and used in nine additional countries. Inducing DL and UL traffic resulted in a substantial increase in exposure, whereas environmental exposure levels remained similar to previous studies. This data is important for epidemiological research and risk communication/management.

1. Introduction

Throughout the years, technology has shaped societies on many different levels: the way we communicate, learn, work, or entertain. The deployment of 5G (5th generation of wireless technology) networks allows for significantly higher data speeds, extremely low latency, more reliability, and higher network capacity (European Commission, 2021). It paves the way for the era of the Internet of Things (IoT) which aims to

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connect all devices and sensors to the network and to facilitate data collection and sharing (Chataut and Akl, 2020).

Switzerland was the forerunner of 5G implementation in Europe with additional frequency bands (i.e., 700 MHz, 1400 MHz, and 3.5 GHz) being auctioned in 2019 (BUNDESAMT FÜR KOMMUNIKATION, 2020). Of particular interest, is the introduction of the 3.5 GHz band, as it allows the implementation of massive Multiple-Input Multiple-Output (Ma-MIMO) antennas. These base stations can configure the amplitude and phase of their antenna elements to ensure constructive interference at the intended location of the user and destructive interference at unintended locations (Thors et al., 2017). The signal-to-noise ratio is therefore maximized by directing a beam towards the user's location, resulting in better communication performances and higher data throughputs. This process is often referred to as beamforming. Beamforming implies that radiofrequency electromagnetic fields (RF-EMF) transmitted from 5G base stations are now highly dynamic in space and time and can vary depending on whether and to what extent people use the network, posing new challenges for RF-EMF exposure assessment studies compared with previous network configurations (Velghe et al., 2021).

Accurate exposure assessment studies are highly important for epidemiological research aiming to evaluate possible health risks associated with RF-EMF exposure. One possible way to estimate exposure to RF-EMF is by implementing microenvironmental surveys. These were first proposed by Röösli et al. (2010) and have since then been used to estimate exposure to RF-EMF from multiple sources in different microenvironments. A microenvironment is defined as a small-scale environment with a distinct function such as a residential area, industrial area, school, public park, or public transport. One main advantage of implementing microenvironmental surveys is that it allows capturing the high spatial variability of RF-EMF in the environment (Röösli et al., 2010). Also, these are conducted by trained researchers, increasing the adherence to the protocol guidelines while controlling for potential issues when carrying the measurement devices, such as body shielding (Bolte, 2016).

Up until now, microenvironmental surveys have focused on measuring environmental downlink (DL) exposure from fixed site transmitters (e.g., mobile phone base stations, television/radio masts) as well as environmental uplink (UL) exposure from other user's mobile phones (Bhatt et al., 2016a, 2016b; Sagar et al., 2018a, 2018b; Urbinello et al., 2014; Velghe et al., 2019). However, neither auto-induced UL exposure, which refers to uplink from own mobile phone, nor the auto-induced component for DL due to beamforming (Deprez et al., 2022; Aerts et al., 2021; Korkmaz et al., 2024) were previously considered. Ignoring this aspect nowadays would result in an underestimation of exposure for a typical person, who is occasionally using a mobile phone and thus generates auto-induced UL and DL.

Velghe et al. (2021) proposed introducing an activity-based approach to microenvironmental surveys where different scenarios of data transmission would be simulated to better understand auto-induced UL and auto-induced DL exposure (Velghe et al., 2021). Measuring all possible scenarios of data transmission would be a cumbersome task, only possible to be applied at a small scale. However, focusing on extreme exposure scenarios allows for comparisons between exposure levels while making it reproducible in larger scale studies.

This study is embedded in the European project GOLIAT (5G expOsure, causaL effects and rIsk perception through citizen engAgemenT), which overarching aim is to characterize and monitor RF-EMF exposure, in particular 5G, provide novel insights into potential causal neuropsychological and biological effects, and understand risk perception and communication through citizen engagement using an integrative and transdisciplinary pan-European approach. In the present study, we propose a protocol to measure extreme scenarios of UL and DL exposure as well as environmental exposure, which was applied in multiple countries participating in the GOLIAT project. This paper describes the measurement protocol in detail and presents the application of the protocol and the measurements conducted in Switzerland. The aims are: i) to present the RF-EMF levels measured in different areas and microenvironments; ii) explore how exposure levels vary between scenarios of data transmission; and iii) investigate which frequency bands contribute the most to total exposure levels in different areas and scenarios of data transmission.

2. Material and methods

The full measurement protocol developed within the GOLIAT framework can be found in Supplementary Information A (SI-A).

2.1. Study design and areas

Five study areas were selected in Switzerland based on the degree of urbanization and population density. The study areas were comprised of two urban (Zürich and Basel) and three rural areas (Hergiswil, Willisau, and Dagmersellen), to account for possible heterogeneity in RF-EMF exposure. Additional details on the criteria for study area selection can be found in SI-A.

Within each study area, a set of microenvironments was defined to assess typical RF-EMF exposure for the general population (Table 1; SI-A, Table S1). The selected microenvironments were grouped into three main categories: outdoor areas, public spaces, and public transport. The outdoor areas were characterized by a walking path in areas of interest within each urban/rural area (e.g., urban/rural centre, residential area, and industrial area). The public spaces consisted of a combination of different indoor and outdoor microenvironments frequented by young people (e.g., schools, universities, public parks, shopping malls, etc.). For both outdoor areas and public spaces, the measurements were conducted in walking mode with an approximate duration of 15 min for each microenvironment. The measurements inside public transport (e.g., bus, tram, metro, or train) were taken when moving between microenvironments. The measurement campaign in Switzerland was conducted between the 20th of February and the April 5, 2023 during working hours (i.e., between 08:00–17:00).

2.2. Measurement devices

Two devices were used to evaluate the RF-EMF exposure and to gather data about the measurement process in the different microenvironments: the ExpoM-RF 4 and a user equipment equipped with a broadband add-on RF-EMF sensor (SI-A, Fig. S1). The ExpoM-RF 4 (Fields At Work, Zurich, Switzerland, http://www.fieldsatwork.ch/) is a personal exposimeter that collects root mean square values from 35 frequency bands in the range from FM to Wi-Fi 5 GHz at a sampling rate of 6.1 s. This allows a detailed characterization of exposure from the major broadcasting and wireless communication services. The frequency bands measured by the ExpoM-RF 4 and the device settings can be found in SI-A, Tables S2–S3.

The user equipment allows testing different scenarios of data transmission. It is equipped with a broadband add-on RF-EMF sensor (Van Bladel et al., 2023) and with the mobile network monitoring software application QualiPoc Android (Rohde & Schwarz, http://www.rohde-schwarz.com/). The sensor is attached to the mobile device through a spring-based phone holder and it measures the power emitted by the phone (in dBm) (SI-A, Fig. S2). The QualiPoc Android application collects cellular network and mobile phone connection parameters relevant for exposure assessment (e.g., technology, frequency bands used, metrics for the received signal, and transmitted power) (Brzozek et al., 2021; Joshi et al., 2017a; Vermeeren et al., 2024). During the measurements, the user equipment was not forced to operate at a specific network technology and only one mobile phone operator was used and thus used in realistic usage mode. In-depth information on the characteristics of the broadband add-on RF-EMF sensor and QualiPoc Android can be found in SI-A, Tables S4–S5. In this study, only RF-EMF

Table 1
Summary statistics (median, interquartile range [IQR], mean, and maximum) of total power flux density (mW/m^2) measured in a given microenvironment.

Microenvironment	Non-user				User max DL exposure				User max UL exposure			
	Nr of samples	Median (IQR)	Mean	Max	Nr of samples	Median (IQR)	Mean	Max	Nr of samples	Median (IQR)	Mean	Max
Zürich												
Industrial area	154	0.81 (0.54–1.15)	0.98	5.46	150	2.18 (1.09–4.09)	2.86	9.40	140	23.76 (12.80–30.86)	22.37	46.24
Shopping mall	192	0.06 (0.03–0.11)	0.10	1.37	Not measured							
Urban business area	194	1.02 (0.46–2.29)	1.60	7.43	178	4.17 (2.53–6.45)	4.67	13.66	178	12.86 (8.58–20.15)	16.18	52.56
Urban centre (downtown)	318	0.22 (0.10–0.49)	0.46	4.88	132	3.20 (1.22–16.07)	9.62	50.35	126	2.80 (0.29–14.95)	19.76	135.04
Urban parks	439	0.14 (0.03–0.22)	0.18	1.11	418	4.07 (1.60–11.17)	7.85	51.85	417	18.24 (4.12–31.36)	18.85	60.80
Urban residential	1485	0.08 (0.05–0.18)	0.16	2.60	446	0.89 (0.41–7.25)	4.94	49.86	432	1.40 (0.58–2.90)	6.25	151.62
Urban schools (primary and high school)	272	0.05 (0.02–0.12)	0.09	0.89	270	3.54 (0.54–12.35)	7.59	42.15	275	0.21 (0.08–3.83)	11.75	142.06
University	146	0.06 (0.03–0.12)	0.12	0.70	146	6.75 (1.64–16.44)	11.24	57.12	147	20.82 (10.23–47.79)	27.24	76.38
Bus station	196	0.15 (0.08–0.24)	0.18	0.80	Not measured							
Train station	323	0.39 (0.22–0.70)	1.00	48.45	Not measured							
Public transports (Bus, tram and train)	2516	0.25 (0.11–0.53)	0.38	11.77	454	1.43 (0.42–5.50)	6.45	102.94	517	5.00 (0.49–24.31)	14.37	117.78
Basel												
Industrial area	162	0.26 (0.08–0.69)	0.59	5.41	165	12.13 (0.40–21.42)	11.86	37.14	149	29.04 (19.37–42.56)	29.21	61.05
Shopping mall	172	0.03 (0.02–0.07)	0.10	1.94	Not measured							
Urban business area	188	0.14 (0.07–0.53)	0.65	9.19	148	1.56 (0.82–3.66)	2.34	8.35	140	12.50 (8.48–24.47)	15.68	33.25
Urban centre (downtown)	137	0.14 (0.06–0.47)	0.54	17.65	130	2.51 (0.74–6.23)	4.56	19.13	137	9.50 (4.02–13.99)	9.65	25.42
Urban parks	419	0.13 (0.06–0.36)	0.28	2.77	431	4.30 (0.90–13.50)	7.52	26.91	419	12.08 (5.07–19.72)	15.11	64.09
Urban residential	891	0.06 (0.03–0.14)	0.13	2.19	389	3.08 (0.99–9.70)	5.95	27.22	436	10.05 (6.24–25.23)	16.20	64.42
Urban schools (primary school)	135	0.03 (0.02–0.06)	0.06	0.92	Not measured							
University	131	0.02 (0.02–0.02)	0.02	0.12	125	9.18 (1.75–13.08)	8.45	18.54	126	14.66 (11.69–18.46)	15.18	34.61
Bus station	353	0.16 (0.08–0.59)	0.52	10.01	Not measured							
Train station	434	0.12 (0.06–0.31)	0.34	13.82	Not measured							
Public transports (Bus, tram and train)	3912	0.23 (0.10–0.52)	0.43	24.83	1522	1.49 (0.52–6.93)	6.71	109.66	1987	6.41 (2.29–13.86)	11.17	111.56
Rural areas[a]												
Industrial area	272	0.18 (0.05–0.49)	0.54	5.12	283	0.44 (0.21–1.84)	1.23	13.77	276	11.45 (2.99–62.04)	28.67	105.97
Shopping mall	139	0.03 (0.02–0.11)	0.10	0.92	Not measured							
Rural centre	443	0.04 (0.03–0.09)	0.10	1.16	430	3.81 (1.04–11.47)	9.58	67.12	422	37.50 (15.19–54.96)	35.36	74.49
Rural parks	370	0.08 (0.04–0.16)	0.11	1.09	378	2.24 (0.49–8.63)	4.98	29.78	389	5.81 (3.98–101.25)	36.03	144.32
Rural residential	431	0.04 (0.03–0.07)	0.09	1.72	415	3.42 (1.01–11.77)	8.93	69.33	422	23.20 (11.18–36.40)	24.02	71.06
Bus station	351	0.07 (0.05–0.10)	0.08	0.65	Not measured							
Train station	426	0.13 (0.06–0.26)	0.19	0.84	Not measured							
Public transports (Bus and train)	489	0.08 (0.05–0.16)	0.13	1.10	528	1.00 (0.25–6.89)	7.46	112.82	381	8.64 (4.92–21.53)	15.05	54.71

[a] Combined measurements in Hergiswil, Willisau and Dagmersellen.

levels measured with the exposimeter ExpoM-RF 4 were investigated.

2.3. Measurement set-up

During the measurement campaign, the researcher wore a backpack carrying the ExpoM–RF 4 and the user equipment. The backpack was designed to minimize body shielding (SI-A) (Loizeau et al., 2023; Bolte, 2016). Inside the backpack, the ExpoM-RF4 was fixed in a case to avoid any movement during the measurements (SI-A, Fig. S3).

The user equipment was set to emulate each specific user scenario and placed in the top pocket of the backpack, guaranteeing a minimum distance of 30 cm from the ExpoM-RF4 to avoid near-field coupling of both devices. The researcher's personal phone was set to flight mode, assuring that its usage did not interfere with the ExpoM-RF 4 measurements.

A diary app built with Open Data Kit (ODK) (Hartung et al., 2010) was installed on the researcher's personal phone and used to record specific information on the time and location of the measurements. More specifically, the diary app recorded information on the country of the measurements, the date, the microenvironment to be measured (e.g., urban centre), the user scenario to be simulated, and the exact start and finish time (HH:MM:SS) of measurements in a given microenvironment.

2.4. Usage scenarios

To understand environmental exposure, auto-induced DL exposure, and auto-induced UL exposure levels, three scenarios of data transmission were simulated.

- Non-user scenario: In this scenario, the user equipment was turned off or set to flight mode. Here, only environmental DL and UL exposure is measured.
- User max DL exposure scenario: In this scenario, the user equipment was set to repeatedly download a 1 GB file from a file transfer protocol (FTP) server, mimicking a scenario of extreme auto-induced DL exposure. In the event of the user equipment being served with a beamforming capable base station, the exposure levels are expected to increase for the 3.5 GHz band in comparison to the non-user scenario. This scenario is hereby referred to as max *DL*.
- User max UL exposure scenario: In this scenario, the user equipment was set to repeatedly upload a file of 500 MB to a FTP server to simulate a scenario of extreme auto-induced UL exposure. This scenario is hereby referred to as max *UL*.

The non-user scenario was measured in all microenvironments a priori defined. The max DL and max UL exposure scenarios were only measured in a subset of microenvironments, as these provide sufficient data traffic to allow comparisons in exposure between the user scenarios (Table 1). With the exception of public transport, measurements for each scenario in a given microenvironment were taken immediately after each other to reduce potential temporal variability between measurements (Aerts et al., 2018).

2.5. Data processing and analysis

2.5.1. Crosstalk correction for the ExpoM-RF 4

Crosstalk is an out-of-band response that occurs when a signal in a given frequency band is unintentionally registered in another frequency band, resulting in double counting. This mainly occurs with bands whose frequencies are very close in the spectrum. In previous studies, crosstalk for the personal exposimeter was reported to occur on the following band pairs: Broadcasting (622–697 MHz) & Mobile UL 700 MHz (700.5–735.5 MHz); Mobile UL 700 MHz & Mobile Supplementary Downlink (SDL) 700 MHz (730.5–765.5 MHz); Mobile SDL 700 MHz & Mobile DL 700 MHz (753–788 MHz); Mobile DL 1.8 GHz (1805–1880 MHz) & DECT (1880–1915 MHz); DECT & Mobile UL 2.1 GHz (1919.5–1994.5 MHz) (Eeftens et al., 2018; Loizeau et al., 2023). In this study, it was identified that particularly during the max DL and max UL scenarios, crosstalk may further occur in one additional band pair: ISM/Wi-Fi 2.4 GHz (2388–2488 MHz) & Mobile UL 2.6 GHz (2497.5–2572.5 MHz) (see Supplementary Information C [SI-C], Fig. S1). To correct for crosstalk, the method developed by Eeftens et al. (2018) (Eeftens et al., 2018) was applied. In sum, the method detects periods where the frequency band pairs are correlated. If the correlation is above a threshold a priori defined (Eeftens et al., 2018; Loizeau et al., 2023), crosstalk is assumed to be present. For frequency bands where a positive correlation is not expected to occur naturally (e.g., DECT – Mobile DL 1.8 GHz; Broadcasting – Mobile UL 700 MHz), a threshold of 0.2 was used. For frequency bands where a positive correlation is expected to occur even without crosstalk (e.g., Mobile UL 700 MHz – Mobile SDL 700 MHz; Mobile SDL 700 MHz – Mobile DL 700 MHz), a threshold of 0.4 was used. Within each crosstalk period, the average ratio between the frequency band pairs is calculated. The stronger signal is identified as the aggressor band, whereas the weaker signal is identified as the victim band. The value of the victim band during the cross-talk period is then replaced by the median exposure value measured in periods where crosstalk is not occurring, whereas the value of the aggressor band remains unchanged (Eeftens et al., 2018) (SI-C, Table S1).

2.5.2. Data cleaning

All entries of the diary app were crosschecked and corrected in the event of mislabeled information (i.e., wrong entries for location or usage scenario) using R software (Foundation for Statistical Computing, version 4.3.2, RStudio Version, 2023.09.1 + 494). The GPS coordinates provided by the ExpoM-RF 4 or QualiPoc Android were used to verify the location of each measurement point.

The measurements for the max DL and max UL scenarios were cleaned using the data gathered from QualiPoc Android. The data was processed through the R&S®ROMES4 Drive Test Software (Rohde & Schwarz, http://www.rohde-schwarz.com/) and Python code. For this, the download and upload (4G and 5G data) throughputs, respectively, were verified for each measurement. If the throughput stayed below 350 kbps (kilobits per second) for at least 30 s and no 3G connection was present, failure of max DL or max UL scenario during those periods was assumed (Supplementary Information B [SI-B], Table S1& Fig. S1) (Stroobandt et al., 2023). This involuntary interruption of the data download or upload could have resulted from different factors (e.g., user equipment reaching high battery temperatures, momentary loss of connection, handover, etc.). In the main analysis, we opted to include the periods of low throughput (analogously to an intention-to-treat analysis) given that this might better reflect exposure in a real-life situation. Nevertheless, all analyses were replicated excluding periods of low throughput, and can be found in SI-B.

2.5.3. Data analysis

The ExpoM-RF4 records data in electric field strength (V/m) with a sampling period of 6.1 s. For all calculations, V/m was transformed to power flux density (mW/m^2). The total RF-EMF power flux density (mW/m^2) was calculated by summing all 35 bands measured by the ExpoM-RF 4 in each sample.

To answer the first two research questions, i.e., how exposure levels vary between the different microenvironments, areas, and usage scenarios, summary statistics (mean, median, interquartile range [IQR], and maximum) for total RF-EMF power flux density were obtained. Boxplots further helped visualizing the full range of RF-EMF values measured.

To understand which frequency bands play a major role in exposure, the mean contribution of each band was calculated and plotted using bar plots. The full range of measured values can be further found in SI-C (Tables S2–S4 & Figs. S2–S4). These were stratified by microenvironment, study area, and usage scenario to better understand how exposure from each given band varied according to these factors. The individual frequency bands for broadcasting, 3.5 GHz, and Wi-Fi 5 GHz were first aggregated within each group (see SI-A, Table S2). All analyses were conducted using R software.

3. Results

3.1. RF-EMF levels measured in different areas, microenvironments, and usage scenarios

The total RF-EMF exposure levels measured with the ExpoM-RF 4 for each microenvironment can be found in Table 1. Across measured microenvironments and study areas, exposure levels tended to be lower during the non-user scenario, followed by the max DL scenario and highest during the max UL scenario (Fig. 1; SI-B, Fig. S2). The average exposure levels in the non-user and max DL scenarios were usually higher in urban areas (i.e., Zürich and Basel) and lower in rural areas. However, for the max UL scenario the opposite was observed, with average higher exposure levels measured in rural areas (Fig. 1).

In Zürich, the highest RF-EMF values during the non-user scenario were measured in the urban business area (median 1.02 mW/m^2; interquartile range [IQR] 0.46–2.29 mW/m^2). In contrast, the highest exposure levels in Basel and in rural areas were found in the industrial area, although these levels were considerably lower than in Zürich. During the max DL scenario, the highest RF-EMF exposure values in Zürich were measured at the university (median 6.75 mW/m^2; IQR

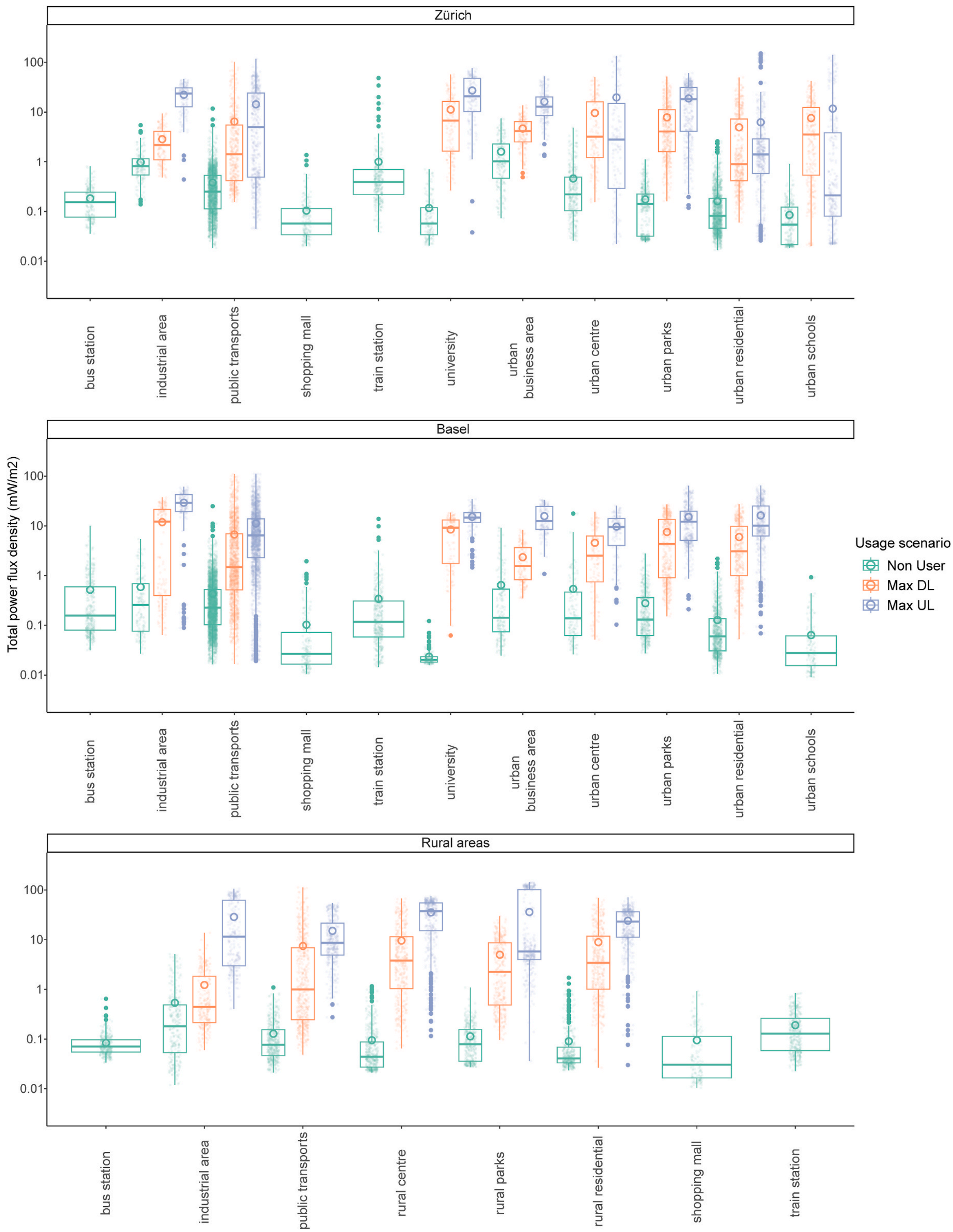

Fig. 1. Boxplot and jitter plots displaying the distribution of the measured total power flux density values (mW/m^2) stratified per microenvironment, usage scenario and area. ° represents the arithmetic mean, horizontal line the median and the box the interquartile range.

1.64–16.44 mW/m^2). In Basel, the highest values were again measured in the industrial area (median 12.13 mW/m^2; IQR 0.40–21.42 mW/m^2), and in rural areas the highest exposure levels were measured in the rural centres (median 3.81 mW/m^2; IQR 1.04–11.47 mW/m^2). Lastly, the highest RF-EMF levels were measured during the max UL scenario, with median exposure levels above 23 mW/m^2 in Zürich and Basel in the industrial areas. In rural areas, the highest exposure levels during the max UL scenario were again measured in the rural centres, with median RF-EMF levels being almost ten times higher than in the max DL scenario (median 37.50 mW/m^2; IQR 15.19–54.96).

3.2. *Contribution of frequency bands to mean total power flux density levels (mW/m^2)*

The mean power flux density (in mW/m^2) for each frequency band or group of bands measured in a given area, microenvironment and usage scenario is presented in Fig. 2. The descriptive statistics can be found in SI-C.

In urban microenvironments (i.e., in Zürich and Basel), the highest mean exposure level during the non-user scenario was typically observed for the Mobile DL 2.1 GHz frequency band (e.g., Zürich urban centre, Basel parks, or residential areas). However, the specific exposure patterns can vary per microenvironment. For instance, in Zürich business area the Mobile DL 800 MHz band (mean 0.44 mW/m^2) was identified as the main contributor to exposure. In universities, one of the microenvironments with the lowest measured levels, the primary contributor to exposure was Wi-Fi 5 GHz (mean 0.02 and 0.01 mW/m^2 in Zürich and Basel, respectively). In rural areas, broadcasting contributed the highest to exposure in different microenvironments during the non-user scenario, with a mean exposure level between 0.03 and 0.04 mW/m^2 in rural parks, bus stations, and rural centre. In other microenvironments of rural areas, such as the industrial areas or train stations, the main contributor to overall exposure was the Mobile DL 800 MHz (mean 0.13 and 0.04 mW/m^2, respectively).

The difference in exposure levels between the non-user and the max DL scenarios for the DL frequency bands was minimal (Fig. 2, SI-C, Figs. S2–S4). However, a significant increase in the 5G Time-Division Duplex (TDD) band (i.e., Mobile TDD 3.5 GHz) was observed during the max DL scenario. Thus, the 5G band was the main contributor to the total mean power flux density values measured during max DL across all study areas. The highest power flux density for the Mobile TDD 3.5 GHz band was measured in Basel's industrial area with a mean of 10.86 mW/m^2, followed by Zürich's university (mean 9.89 mW/m^2). However, it is important to note the wide distribution of values measured in this frequency band, with some high peaks in exposure contributing to an overall increase of the mean power flux density (SI-C Figs. S2–S4). In rural industrial areas, the main contributor to exposure during the max DL scenario was the Mobile UL 2.1 GHz frequency band (mean 0.57 mW/m^2), in the absence of Mobile TDD 3.5 GHz band. Also, substantially lower values were measured in this microenvironment.

During the max UL scenario, the Mobile UL 2.1 GHz and the Mobile TDD 3.5 GHz frequency bands were the main contributors to exposure in urban areas, with similar mean power flux density levels. Additionally, it was observed that in certain microenvironments in Zürich, including industrial areas, universities, and urban parks, the Mobile UL 2.6 GHz also contributed significantly to the overall exposure levels (with mean values of 17.09 mW/m^2, 7.55 mW/m^2, and 4.18 mW/m^2, respectively). In rural areas, the mean power flux density was substantially higher for the Mobile UL 2.1 GHz compared to the Mobile TDD 3.5 GHz frequency bands across microenvironments. For example, in rural parks, the Mobile UL 2.1 GHz (mean 33.25 mW/m^2) contributed to more than 90% of the total mean power flux density measured in this microenvironment. The Mobile TDD 3.5 GHz only contributed to exposure in the rural centres and rural parks, while in the remaining rural microenvironments the mean power flux density remained unchanged compared to the non-user scenario (SI-C, Table S4).

4. Discussion

To the best of our knowledge, this is the first study applying an activity-based component to microenvironmental surveys in order to disentangle environmental from auto-induced DL and UL RF-EMF exposure. In this paper, data from Switzerland is presented to demonstrate the suitability of the measurement protocol, as it was the forerunner of 5G implementation in Europe (BUNDESAMT FÜR KOMMUNIKATION, 2020). We found that RF-EMF exposure levels are substantially higher while inducing DL and UL traffic. We observed a trend showing that RF-EMF exposure levels during max DL tended to increase compared to the non-user scenario, due to the Mobile TDD 3.5 GHz frequency band, particularly in urban settings. Conversely, during the max UL scenario, RF-EMF exposure levels were highest in rural settings mostly due to the Mobile UL 2.1 GHz band.

In Switzerland, similar RF-EMF exposure levels around 0.1 mW/m^2 were observed in previous microenvironmental surveys when measuring environmental exposure levels (Loizeau et al., 2023; Sagar et al., 2018b). Higher RF-EMF levels measured in urban areas compared to rural areas, are also in line with earlier research conducted in Switzerland (Loizeau et al., 2023), Belgium (Bhatt et al., 2016a; Vermeeren et al., 2013), France (Chikha et al., 2024), and Australia (Bhatt et al., 2016a, 2024). This is to be expected due to the dense base station network in more populated areas to serve the demands of numerous users. The main source of environmental exposure across study areas is attributed to DL frequency bands (Loizeau et al., 2023; Bhatt et al., 2016a; Velghe et al., 2019; Sagar et al., 2018b), with mid-band DL frequency bands (e.g., Mobile DL 2.1 GHz) measured the highest in urban areas and low-band DL frequency bands (e.g., Mobile DL 800 MHz) in rural areas. Lower frequency bands provide superior wide-area coverage, which is particularly advantageous in rural settings, whereas mid-frequency bands facilitate the transfer of greater amounts of data at higher speeds, which is beneficial in urban areas. However, it is important to note that most of the microenvironments selected in this study were in outdoor environments, therefore explaining the high contribution of DL bands from mobile phone base stations. It is likely that in indoor microenvironments, other sources (e.g., UL sources from nearby users, DECT or Wi-Fi) will further contribute to exposure (Sagar et al., 2018b; Vermeeren et al., 2013; Jalilian et al., 2019).

Our results further show substantially higher exposure for auto-induced DL compared to environmental exposure. The increased exposure in the max DL scenario is mainly attributed to the 5G frequency band at 3.5 GHz, as a priori expected. In Switzerland, the launch of 5G networks started in 2021 and by 2023, over 90% of the population had access to 5G services (Eidgenössische Kommunikationskommission., 2023). Moreover, the 5G base stations are equipped with Ma-MIMO technology with beamforming capabilities, directing the signal toward the user, ultimately resulting in higher exposure levels when inducing downlink traffic (Aerts et al., 2021, 2023; Deprez et al., 2022). However, the contribution of the 5G band during max DL is almost four times higher than what was previously reported by Aerts et al. (2021) for spot measurements using spectrum analyzer in Bern, Switzerland. In this context, it is important to note that the Mobile TDD 3.5 GHz band uses time-division communication links (i.e., UL and DL signals are separated by the allocation of different time slots) that cannot be distinguished by the ExpoM-RF 4 (Aerts et al., 2021). This means that the contribution of the 5G band to the total exposure is not only a result of beamforming but also influenced by the UL contribution of the TDD scheme, since the emitting user equipment is only 30 cm away from the measurement device. In line with this, we observed that UL bands (namely Mobile UL 2.1 GHz) are somewhat increased during the max DL scenario. Further research understanding the influence of the user equipment proximity to the ExpoM-RF 4, or the influence of time slots of the TDD scheme dedicated exclusively to DL purposes (Lee et al., 2021) is needed to better comprehend the true contribution of beamforming in auto-induced DL exposure.

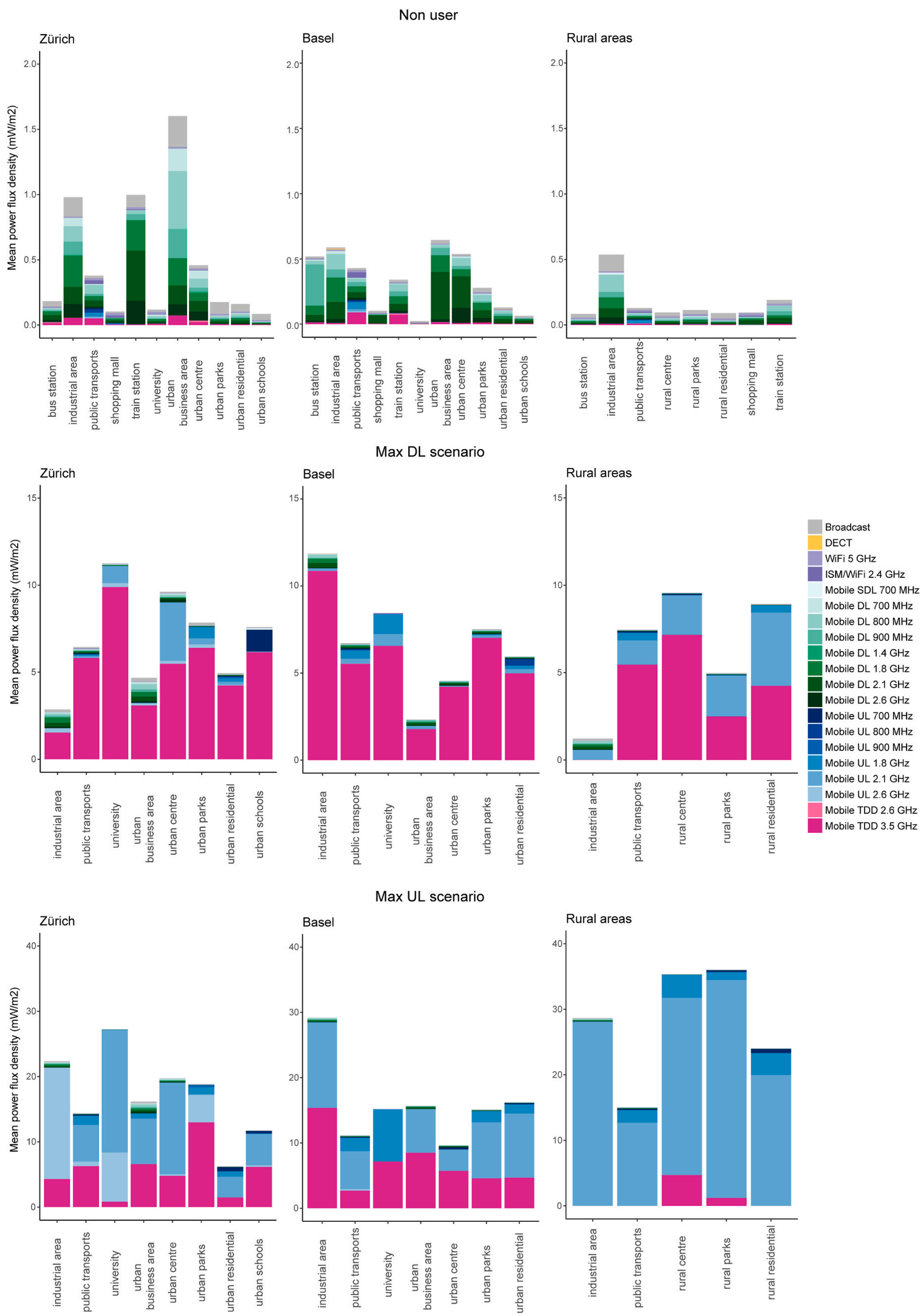

Fig. 2. The bar plot illustrates the mean power flux density values (mW/m^2) of each frequency band, providing a detailed view of the variation across different microenvironments.

The highest RF-EMF levels were measured during the max UL scenario, particularly evident in rural areas. Previous studies have demonstrated significant variations in the output power of mobile phones across different environments. Specifically, rural areas tend to exhibit higher average output power levels compared to urban settings (Joshi et al., 2017b; Persson et al., 2012; Hillert et al., 2006; Lönn et al., 2004), which can then translate into higher RF-EMF levels measured. This is likely due to the poorer received signal quality from base stations in such areas (Brzozek et al., 2021; Vermeeren et al., 2024; Lönn et al., 2004). The frequency bands measured the highest during this scenario were the Mobile TDD 3.5 GHz (mainly in urban areas) and Mobile UL 2.1 GHz, which could be a result of 4G-5G dual connectivity or non-standalone 5G networks, where both 4G and 5G frequency bands are used simultaneously. This allows a considerable increase in user throughput while maintaining mobility robustness by enabling the user equipment to connect at the same time to two cells (Agiwal et al., 2021). In rural settings, the user equipment used mostly mid-band frequencies for upload purposes (i.e., Mobile UL 2.1 GHz and Mobile UL 1.8 GHz), while the 5G frequency band contributed less to exposure. One possible explanation for this is the larger distance of the user equipment to the base stations in these areas, a result of the relatively low base station density (Joshi et al., 2017b).

For the interpretation of the UL measurements during the max UL scenario, one needs to keep in mind that the measurement device was about 30 cm away from the emitting user equipment. This implies that for a realistic mobile phone user, RF-EMF exposure of body parts close to the user equipment is at least one order of magnitude higher, whereas further distant exposure (e.g., at feet level) is substantially lower. Further, the scenarios of data transmission used in this study, represent extreme minimum (non-user scenario) and maximum (max DL & max UL) exposure cases, which do not always represent a real-life exposure scenario. Hence, further studies are needed to understand exposure in more realistic scenarios of data transmission and in-situ duty cycles can be used to obtain realistic values for various applications (Vermeeren et al., 2024).

5. Strengths and limitations

Our study has three main strengths: (i) we described in detail a study protocol to apply activity-based microenvironmental surveys in multiple European countries. This will allow further characterization of RF-EMF exposure patterns in Europe; (ii) this is the first microenvironmental study that aims to disentangle environmental from auto-induced DL and UL exposure, allowing to characterize RF-EMF exposure levels in the era of 5G; (iii) we explored RF-EMF exposure levels in different areas with different degrees of urbanization. Moreover, it was possible to ascertain which frequency bands are primarily responsible for exposure in diverse microenvironments and scenarios of data transmission. This is of relevance to future dose model studies that use an integrative approach with multiple near-field and far-field sources to understand cumulative RF-EMF dose absorption in specific organs or the whole body (Liorni et al., 2020; van Wel et al., 2021; Birks et al., 2021).

There are also noteworthy limitations. First, the backpack used during the measurement campaign was designed to minimize body shielding. However, it is not possible to discard the interference of body shielding, which could lead to an underestimation of the measured RF-EMF levels (Chikha et al., 2024; Bolte, 2016). Second, the temporal resolution of the ExpoM-RF 4 device may introduce uncertainty on the measured exposure levels given that each frequency band is only observed for 50 ms every 6.1 s. In this study, we minimized the uncertainty by measuring each microenvironment over 15 min, which was previously found to provide highly reproducible mean values per microenvironment (Sagar et al., 2016). For the max DL and max UL exposure scenarios, this is likely to be less critical. However, for other scenarios of data transmission with higher temporal variability (e.g., voice call, ping test), this uncertainty may be significant and warrants further investigation. Third, due to the TDD scheme of the 5G frequency band, it is not possible to distinguish between DL and UL signals emitted at this frequency. This makes it difficult to differentiate between exposure from the emitting mobile phones and from beamforming due to auto-induced DL traffic. To study biological effects, this differentiation is not necessary although it would be useful for dosimetry modelling. For risk communication, it may be sufficient to differentiate between environmental and auto-induced exposure (UL and DL), since the first is involuntary and the latter self-induced except if one is a bystander of a mobile phone user. Lastly, in this study, only one user equipment and mobile phone provider were investigated. Therefore, these results cannot be generalized (especially when looking into the contribution of different frequency bands to total exposure) as this is likely dependent on the user equipment and mobile phone provider (Lee and Choi, 2019) Our measurement results from other nine European countries will help in understanding variations in exposure to different frequency bands between countries.

6. Conclusion

A novel activity-based microenvironmental survey protocol was developed and successfully carried out to disentangle environmental from auto-induced downlink and uplink exposure in the era of 5G. The measurements conducted in Switzerland demonstrate that higher RF-EMF exposure levels were measured when inducing maximum downlink and uplink traffic using a user equipment, with the 5G band at 3.5 GHz and the UL band at 2.1 GHz the main contributors to exposure, respectively. This data is important for epidemiological research, risk communication and risk management, but also for future dosimetry and modelling studies. Future research understanding auto-induced DL and UL exposure from more realistic case scenarios remains necessary for a better characterization of the exposure levels. Future research will consist of the application of the proposed protocol in various countries and the comparison of the exposure values.

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CRediT authorship contribution statement

Adriana Fernandes Veludo: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Bram Stroobandt:** Writing – review & editing, Formal analysis, Data curation. **Han Van Bladel:** Writing – review & editing, Formal analysis, Data curation. **Nekane Sandoval-Diez:** Writing – review & editing, Formal analysis. **Mònica Guxens:** Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization. **Wout Joseph:** Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization. **Martin Röösli:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Conceptualization.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.120550.

Data availability

Link to the repository containing raw data and codes will be shared in a later stage after review

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