Journal of Exposure Science & Environmental Epidemiology (2021) 31:999–1007
https://doi.org/10.1038/s41370-021-00287-8

ARTICLE

Radio-frequency electromagnetic field exposure and contribution of sources in the general population: an organ-specific integrative exposure assessment

Luuk van Wel[1] · Ilaria Liorni[2] · Anke Huss[1] · Arno Thielens[3,4] · Joe Wiart[5] · Wout Joseph[3] · Martin Röösli[6,7] · Milena Foerster[6,7] · Amelie Massardier-Pilonchery[8,9] · Myles Capstick[2] · Elisabeth Cardis[10,11,12] · Roel Vermeulen[1]

Received: 24 February 2020 / Revised: 6 January 2021 / Accepted: 6 January 2021 / Published online: 2 March 2021

Abstract
In order to achieve an integrated radio-frequency electromagnetic fields (RF-EMF) dose assessment, detailed information about source-specific exposure duration and output power is needed. We developed an Integrated Exposure Model (IEM) to combine energy absorbed due to use of and exposure to RF-EMF sources and applied it to a sample of the general population to derive population RF-EMF estimates. The IEM used specific absorption rate transfer algorithms to provide RF-EMF daily dose estimates (mJ/kg/day) using source-specific attributes (e.g. output power, distance), personal characteristics and usage patterns. Information was obtained from an international survey performed in four European countries with 1755 participants. We obtained median whole-body and whole-brain doses of 183.7 and 204.4 mJ/kg/day. Main contributors to whole-brain dose were mobile phone near the head for calling (2G networks) and far-field sources, whereas the latter together with multiple other RF-EMF sources were main contributors for whole-body dose. For other anatomical sites, 2G phone calls, mobile data and far-field exposure were important contributors. The IEM provides insight into main contributors to total RF-EMF dose and, applied to an international survey, provides an estimate of population RF-dose. The IEM can be used in future epidemiological studies, risk assessments and exposure reduction strategies.

Keywords RF-EMF · Mobile communication devices · Dose estimation · Modelling

Introduction

Radio-frequency electromagnetic fields (RF-EMF) are used extensively in modern society to facilitate wireless communication. This has led to health concerns regarding

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41370-021-00287-8.

✉ Roel Vermeulen
R.C.H.Vermeulen@uu.nl

1 Institute for Risk Assessment Sciences (IRAS), Utrecht University, Yalelaan 2, 3584 CM Utrecht, The Netherlands

2 Foundation for Research on Information Technologies in Society (IT'IS Foundation), Zeughausstrasse, 43, 8004 Zurich, Switzerland

3 Department of Information Technology, Ghent University, IMEC, Waves Research Group, Ghent 9052, Belgium

4 Department of Electrical Engineering and Computer Sciences, University of California Berkeley, Berkeley Wireless Research Center, Berkeley, CA 94704, USA

5 Chair C2M, LTCI Télecom Paris, Institut polytechnique de Paris, Paris, France

6 Swiss Tropical and Public Health Institute, Basel 4051, Switzerland

7 University of Basel, Basel, Switzerland

8 Université de Lyon, Université Claude Bernard Lyon, Ifsttar, UMRESTTE, UMR T_9405, 8 Avenue Rockefeller, 69373 Lyon, France

9 Centre Hospitalier Lyon Sud, Hospices Civils de Lyon, 69495 Pierre Bénite, France

10 Barcelona Institute for Global Health (ISGlobal), Barcelona, Spain

11 Universitat Pompeu Fabra (UPF), Barcelona, Spain

12 CIBER Epidemiología y Salud Pública (CIBERESP), Madrid, Spain

potential short- and long-term effects of RF-EMF in the general population [1]. An accurate exposure assessment including all major RF-EMF sources is required to address these concerns. Previously, self-reported device use, data from mobile phone network operators and wave propagation models have been used to estimate exposure and were often limited to one or a few RF-EMF sources [2–4]. However, the proliferation of novel devices together with the continuing evolution and uptake of RF-EMF technologies have led to a rapidly expanding spectrum of sources that need to be considered, ranging from smartphones and wearables to Wi-Fi networks and modern cellular base stations. In addition, for personal devices the patterns of use are often an important determinant in RF-EMF dose: a mobile phone held near the head during a phone call will result in a different exposure pattern compared to that induced by a tablet placed on the lap while streaming videos. These aspects have made RF-EMF exposure assessment a daunting effort [5, 6]. Preferably, a series of realistic population exposure scenarios would be available for application in risk assessment and (if appropriate) risk mitigation, where relevant RF-EMF sources and the contribution of each to total exposure are included for various exposed groups. An integrative model including multiple sources is therefore needed to estimate RF-EMF exposure in the population. Previously, both Roser et al. [7] and Lauer et al. [8] developed models combining near-field and far-field exposure. However, the devices included in these models were limited to mobile phones, Digital Enhanced Cordless Telecommunications (DECT) phones and far-field sources. Exposure was estimated for the brain and whole body (Lauer et al.) and also additional anatomical sites of the brain (Roser et al.), but no anatomical sites in other parts of the body. These models do not include all current prevalent RF-EMF sources, technologies and use patterns such as smartwatches worn throughout the day, or tablets, which are used away from the head. Ideally, a model would include current and near future RF-EMF sources, multiple anatomical sites throughout the body (to account for devices being held away from the head) and the ability to vary duration of use and multiple output powers depending on the device functions used.

To close this gap, we designed an Integrated Exposure Model (IEM) to include many relevant current and near future sources, based on specific absorption rate transfer algorithms (SAR) developed by Liorni et al. [9] (a brief explanation can be found in Supplementary Materials A). The IEM was applied to a European survey on mobile device use to estimate population RF-EMF exposure scenarios. The results provide detailed estimates of population-wide exposure levels and the contribution of various RF-EMF sources to these levels, which can in turn be used as input for future epidemiological investigations, risk assessment and exposure reduction strategies.

Methods

RF-EMF Integrated Exposure Model

The IEM estimates the integrated daily dose for multiple anatomical sites, including the whole body, different organs (e.g. brain, heart) and tissues and more specific locations (e.g. individual brain regions) in millijoules per kilogram per day (mJ/kg/day). Outputs in other units of time (e.g. monthly, yearly) are also possible, as well as a cumulative dose (J/kg-years). This is based on exposure from near-field (the distance from the source is smaller than one wavelength), near-to-far-field (the distance from the source is larger than one wavelength and smaller than two wavelengths), and far-field (the distance from the source is larger than two wavelengths) RF sources. The model takes into account source-specific attributes (source type, output power), personal characteristics (age, sex, body mass, height) and the way devices are being used (position relative to the body, type of use, duration of use). This allows for better dose estimation and insight in the contribution of different sources and uses to the total RF-EMF dose received. A detailed explanation of the IEM can be found in Supplementary Materials A.

Input information

Device use information in the population was obtained from the Mobile Device Use Survey (CREST project, 2013) [10]. Recruitment took place from October 2016 to April 2017 in four European countries: France, the Netherlands, Spain and Switzerland. A random sample of 10,000 house addresses was taken in each country, resulting in 40,000 addresses overall. An invitation for one participant per household was sent to each address with a token to access the survey. Responses from participants younger than 18 years were deleted due to ethical constraints. Ethical approval by the respective Institutional Review Boards was obtained in France, the Netherlands, Spain and Switzerland. In the Netherlands, a small incentive was offered to increase participation (lottery of gift cards of €40). In Spain, additional volunteers were requested from the research institute's volunteer program. The survey contained detailed questions concerning multiple mobile devices, allowing for the creation of detailed scenarios of use in the IEM. Questions included frequency and duration of use, number of devices used on a regular basis and the use of mobile phones and tablets in particular. For mobile phones and tablets, functions used on the devices (e.g. phone calls, streaming audio),

Table 1 Absolute dose in (mJ/kg/day) for whole-body and whole-brain.

Source	Whole-body (mJ/kg/day)				Whole-brain (mJ/kg/day)			
	P_5[a]	Median	P_{95}[a]	Mean	P_5[a]	Median	P_{95}[a]	Mean
Overall	**80.1**	**183.7**	**867.3**	**290.4**	**85.0**	**204.4**	**3323.7**	**810.5**
Near-field, total	5.3	98.7	756.0	199.3	5.1	105.1	3235.1	719.6
Phone near head, 2G	0.0	5.3	236.8	49.0	0.0	70.4	3168.7	656.1
Phone near head, 3G	0.0	0.1	3.9	0.8	0.0	1.2	51.9	10.7
DECT phone near head	0.0	0.3	2.4	0.9	0.0	4.5	31.9	11.9
Phone with HFK[b]	0.0	0.0	343.0	37.9	0.0	0.0	1.5	0.2
Phone data	0.0	4.1	224.5	46.5	0.0	2.2	112.4	23.9
Tablet	0.0	0.2	212.8	42.6	0.0	0.0	59.3	13.3
Laptop	0.0	4.9	77.8	20.5	0.0	0.6	10.1	2.2
Body area network	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1
Smartwatch	0.0	0.0	2.9	0.5	0.0	0.0	0.0	0.0
Virtual reality headset	0.0	0.0	0.0	0.4	0.0	0.0	0.0	1.2
Near-to-far-field, total	28.3	28.3	28.3	28.3	13.6	13.6	13.6	13.6
Wi-Fi-router	28.3	28.3	28.3	28.3	13.6	13.6	13.6	13.6
Far-field, total	29.6	56.6	124.0	62.8	36.1	68.4	121.8	77.3
Downlink	8.3	24.1	42.2	24.1	11.3	37.1	52.9	33.1
Uplink	10.1	15.7	23.3	15.9	15.3	22.6	29.6	21.6
Broadcast	4.9	12.0	53.6	19.2	2.6	7.7	16.8	8.2
DECT	0.5	1.3	4.3	1.9	0.6	5.1	34.0	13.0
Wi-Fi	1.0	1.9	2.5	1.7	0.7	1.4	1.8	1.3

[a] P_5 and P_{95} are the 5th and 95th percentile, respectively.

[b] Hands-free kit.

the position in which the device was mainly held, the main location of use (i.e.: work, home, school, transit) and frequency and duration of use of those functions were asked. The complete questionnaire can be found in Supplementary Materials B.

Output powers derived either from the literature or based on expert opinion (JW, WJ, MC) were assigned to each device and—if available—function of the device (Table 1). Values for the various mobile phone and tablet functions were obtained from average Wi-Fi duty cycles determined by ref. [11], assuming a network speed of 6 Mbps. The output power of the device depends on the function it was used for.

Additional input data

Some information was not available from the survey. Minutes of DECT calls per day were imputed using data from the AMIGO study, where subjects were asked for the duration of DECT calls in minutes per week (categorized) [12]. The average value of each category was assumed and matched to participants based on age and sex. Far-field exposure information was obtained from the GERoNiMO personal exposure measurement survey where participants carried an exposure monitor for 24–72 h [13]. Data were collected on 16 frequency bands, between September 2014 and February 2016, in Switzerland, Slovenia, Spain, Denmark and the Netherlands. In this study, the results were time-weighted (dividing the 24 h day in 2 h slots and taking the average of each slot), resulting in a single time-weighted average per participant. Swiss, Spanish and Dutch results were used by taking the average result over all participants in each respective country. For French participants, the average over all five countries was used (Table 1). The duration of far-field exposure was set to 1440 min (i.e. continuous exposure throughout 1 day) (Table 2). Height and mass proxy data were used from Statistics Netherlands (CBS) [14], the Swiss Gesundheidsbefragung 2012 [15] and Special Eurobarometer 246 [16] (Supplementary Table A.3).

No information was available concerning the presence of Wi-Fi routers nearby (e.g. same room or building). It was assumed that each participant was in the near-to-far-field of a Wi-Fi router for 1 h per day, with an estimated average output power of 5 mW. European average network operator values were derived from the 'Mobile Phone Operator Questionnaire' from the MOBI-Kids study (data not published) (2015), assuming 55% of all call minutes to be spent on 2G network and the remaining 45% spent on 3G networks. The model could not include calls on 4G networks. There was no information available concerning laterality (i.e. is the phone held on the left or right side of the head).

Table 2 Durations of use for different sources per day, in minutes.

Source	P_5[a]	Median	P_{95}[a]	Mean
Near-field				
Phone near head, 2G	0	0.6	24.8	5.1
Phone near head, 3G	0	0.5	20.3	4.2
DECT phone near head[b]	0	2.4	17.1	6.4
Phone headset	0	0	18	1.7
Phone data	0	19.1	218.6	47.0
Tablet	0	1.0	137.9	29.6
Laptop	0	30	480	126.6
Body area network	0	0	0	4.1
Smartwatch	0	0	120	22.0
Virtual reality headset	0	0	0	0.2
Near-to-far-field				
Wi-Fi-router	60	60	60	60
Far-field				
Far-field[c]	1440	1440	1440	1440

[a] P_5 and P_{95} indicate 5th and 95th percentiles, respectively. Arithmetic mean.

[b] DECT phone information was obtained from the AMIGO study.

[c] Exposure to far-field was assumed to be constant throughout the day, resulting in 1440 min (i.e. 1 day).

Previously we have found significant recall error in comparing self-reported versus recorded laterality amongst adolescents. It was therefore assumed to be 50% of the total time on each side of the head [17]. As the Mobile Device Use Survey contained categorical questions, the centre point of each category was used as the duration in minutes. For the open top categories stating 'more than *x* minutes' we multiplied the lower category bound by (5/3) as previously described for assigning mid-points to open bounded categories [18]. For some functions (e.g. texting), only the frequency of use was asked. A set amount of time was assumed for those functions based on estimations of the actual data transmission time involved. One SMS message was assumed to be 0.1 s of data transmission, one video message 10 s, uploading a photo or video 30 s and streaming audio/video or playing an online game 300 s.

Statistical analysis

An RF-EMF dose estimate was obtained for every participant of the population survey, using the IEM. The median, mean, 5th and 95th percentiles from this sample of individual estimates were used to provide insight into the dose as well as the variation within the population. Results were stratified for age, sex and country of origin. Relative contributions of individual sources to total integrative dose were calculated per participant and consequently shown as percentile distributions using boxplots. The model was written in the open-source programming language R. All analyses were performed using R version 3.4.1. [19].

Sensitivity analyses

As there was no information on the amount of time spent in range of the near-to-far field of a Wi-Fi router, we assumed 1 h of exposure for each participant. Two sensitivity analyses were performed to assess the influence of this assumption. In the first analysis (1) half an hour of exposure (50%) was assumed instead, and in the second analysis (2) 2 h of exposure (200%) was assumed.

Results

Mobile Device Use Survey

A total of 1755 participants from four countries (Switzerland (388, 22.1%), Spain (321, 18.3%), France (478, 27.2%) and the Netherlands (568, 32.4%)) completed the survey. The number of male (50.8%) and female (49.2%) respondents was nearly identical. The average age was 54 years (range 40–65 years), with 6.9% being 25 years or younger and 22.6% older than 65 years. The complete age distribution can be seen in Supplementary Fig. A.7. A total of 1223 (69.6%) of participants obtained a college level or higher education. The duration of use varied between devices, with laptop use, tablet use and mobile phone use, other than calling, having the longest use times. Most participants reported using a mobile phone at least once during the last 3 months (96.7%), followed by a laptop (66.5%) and tablet (56.5%). The use of other devices was significantly less common: activity trackers were used by 4.9% of all respondents, smartwatches by 3.1%, body worn sensors (i.e. body area networks, medical sensors) by 2.1% and virtual reality headsets by 1.8%. The use of various device functions was asked for tablets and mobile phones, details of which (both overall and stratified for age) can be found in Supplementary Table A.4. These details show a wide variety in the functions being used, with higher age categories generally using less functions of these devices. The main uses were phone calls and internet browsing for mobile phones and tablets, respectively. The duration of use for the respective devices is illustrated in Table 2.

IEM results

Integrated dose

The median whole-body and whole-brain doses of our population within the CREST survey were 183.7 (p5–p95: 80.1–867.3) mJ/kg/day and 204.4 (p5–p95:

85.0–3323.7) mJ/kg/day, respectively. For whole-body exposure far field of telecommunications and multiple other sources played a prominent role, while for the whole-brain the near-field sources were dominant. In both instances, the near-to-far-field exposure to Wi-Fi routers was the third of the three main categories (i.e.: near, near-to-far, far-field). Variation in doses was largest for near-field sources: while every participant has at least some exposure from near-field sources, the type of source contributing varies strongly as can be seen by the low median values per source (Table 1).

Country, age and sex-specific differences

The total dose for both the whole-body and whole-brain differed between countries, with Spanish participants having the highest estimated dose for both: nearly double of the overall median result. This appears to be driven by both higher near-field and far-field exposure. Conversely, French participants received doses well below the overall median. This could be an effect of the different age distributions between countries, with Spanish participants being younger and French participants being older on average. Stratified by age, the highest median doses were seen for participants between 30 and 39 years old. No significant difference was observed between male and female participants (Table 3).

Relative contribution of sources

The distribution of RF source contributions differed between whole-body and whole-brain dose (Fig. 1). Whole-brain dose was dominated by mobile phone use at 2G networks, followed by nearby Wi-Fi-routers. Mobile phone calls were less relevant for whole-body exposure; however, Wi-Fi-routers, laptops, tablets and other phone use contributed more. A log scaled version of results shown in Fig. 1 is provided to be able to distinguish sources providing lower levels of contribution (Supplementary Fig. A.2). The relative contributions for the other anatomical sites can be found in Supplementary Table A.8 in the form of a heat map.

Contribution of specific functions

Looking at mobile phone functions, voice calls without hands-free kit were the dominating contributor to whole-brain dose, with only marginal contributions from other functions. For whole-body dose browsing, uploading data and streaming videos are present as well (Fig. 2). Looking at the relative contribution of tablet functions, little difference was observed between whole-body and whole-brain. Browsing the internet and streaming videos are the most relevant functions for tablet use (Fig. 3), while calls dominate mobile phone use (Fig. 2). In addition, Figs. 2 and 3 can be viewed on a log scale as Supplementary Figs. A.3 and A.4 for more details on the other functions.

Sensitivity analyses

Two sensitivity analyses were performed by modifying the Wi-Fi-router exposure duration. Total dose from Wi-Fi-router exposure is reduced by 50% and raised to 200% when respectively lowering by half or doubling the estimated time spent within the presence of an active Wi-Fi router. For relative contributions, halving the dose brings the dose contribution on the same level as far-field exposure. Full details can be found in Supplementary Tables A.6, A.7 and Supplementary Figs. A.5, A.6.

Discussion

We designed the most comprehensive RF-EMF dose estimation tool to date, capable of estimating RF-EMF dose from near-field, near-to-far-field and far-field sources. We applied this IEM to an international survey on mobile device use in four European countries in order to obtain population RF-EMF exposure profiles. The median dose was found to be 183.7 (p5–p95: 80.1–867.3) mJ/kg/day and 204.4 (p5–p95: 85.0–3323.7) mJ/kg/day for whole-body and whole-brain, respectively. The median dose varied per country and per age group, with overall doses found to be higher in younger age groups for both the whole-body and the whole-brain. Looking at the relative contribution of sources, mobile phone calls near the head were the main contributor for whole-brain dose followed by far-field sources and a smaller contribution of nearby Wi-Fi-routers. For the whole-body dose contributions, on the other hand, far-field telecommunication sources together with other sources (Wi-Fi-routers (in the near-to-far-field), laptops, tablets and other mobile phone functions than calls) provided higher contributions. For other anatomical sites, the dose is driven by relative contributions from phone and tablet data use, far-field sources and Wi-Fi-routers. This illustrates the importance of taking multiple RF-EMF sources into account when looking at anatomical sites other than the brain, for instance potential health endpoints in organs such as the heart, liver or pancreas related to devices held in different positions around or on the body.

Strengths and limitations

Main strengths of our model include the large number of RF-EMF sources and anatomical sites included: both nearby and further away sources can be assessed, and dose estimates are available for many anatomical sites besides the whole-brain and specific brain regions. The ability to include as many

Table 3 Median dose (mJ/kg/day) and interquartile range (IQR) per source group, stratified for age, sex and country.

	N	Near-field	Near-to-far-field[a]	Far-field	Total
Whole-body (mJ/kg/day) Median (IQR)					
Overall	1755	98.7 (23, 211.1)	28.3 (–)	56.6 (46.8, 67.7)	183.7 (105.8, 313.8)
Country					
France	478	27.4 (8.1, 116)	28.3 (–)	59.7 (57.3, 67.7)	121.2 (100.6, 207.5)
Netherlands	568	106.9 (27.3, 251.5)	28.3 (–)	50.3 (47.3, 56.6)	188.1 (108.3, 334.4)
Spain	321	152.9 (57.7, 351.8)	28.3 (–)	119.5 (105.5, 124.4)	302.1 (208.6, 502.8)
Switzerland	388	99.4 (24.8, 197.9)	28.3 (–)	33.5 (29.9, 35.7)	161.1 (82.9, 260.9)
Age					
18–29 years	180	177.4 (83.1, 425.4)	28.3 (–)	61.7 (38, 129.2)	294.6 (191.1, 516.7)
30–39 years	208	176.3 (100, 422.9)	28.3 (–)	59.9 (49.4, 123.5)	295.8 (189, 545.1)
40–49 years	245	126.8 (36.2, 300.6)	28.3 (–)	56.9 (47.9, 101.3)	223.5 (139.5, 402.2)
50–59 years	316	86 (21.3, 179.3)	28.3 (–)	55.6 (36.4, 59.1)	168.2 (103.4, 266.6)
60–69 years	425	39.3 (11.1, 126.2)	28.3 (–)	56.4 (46.5, 65.2)	131.1 (97.6, 209)
70+ years	220	24.8 (6.9, 97.1)	28.3 (–)	56.4 (48.5, 59.2)	108.9 (90.6, 181.3)
Sex					
Male	892	95.5 (19.6, 183.8)	28.3 (–)	49.3 (46.5, 57.3)	171.8 (97.8, 265.8)
Female	863	104.5 (25.9, 255.2)	28.3 (–)	63.7 (55.6, 75)	197.3 (117.5, 357.8)
Whole-brain (mJ/kg/day) Median (IQR)					
Overall	1755	105.1 (75.4, 1298.8)	13.6 (–)	68.4 (63.5, 94.7)	204.4 (150.5, 1377.5)
Country					
France	478	76.9 (16.2, 1290.1)	13.6 (–)	68.6 (64.9, 76.1)	159.5 (108.8, 1369.4)
Netherlands	568	113.9 (76.6, 1300.8)	13.6 (–)	67.3 (63.5, 69.8)	205 (156.9, 1381.9)
Spain	321	207.3 (90, 1319.8)	13.6 (–)	103.3 (101.1, 108.5)	350.4 (210.4, 1440.5)
Switzerland	388	107.6 (77.1, 1300.4)	13.6 (–)	39.9 (38.9, 50.9)	186 (130.6, 1354.6)
Age					
18–29 years	180	207.6 (91.5, 1311.3)	13.6 (–)	69.8 (43.4, 103.3)	301.3 (187.6, 1415.8)
30–39 years	208	288.7 (104.9, 1325)	13.6 (–)	74.7 (64.2, 103.5)	431.3 (207.2, 1433.8)
40–49 years	245	162.7 (79.9, 1319.7)	13.6 (–)	69.8 (64.2, 101.1)	270.8 (158, 1420.4)
50–59 years	316	91.5 (73.4, 1300.3)	13.6 (–)	67.3 (62.8, 74.7)	185.5 (136.7, 1380.9)
60–69 years	425	83.5 (72.7, 1290.3)	13.6 (–)	67.3 (63.5, 74.7)	165.3 (147.5, 1364.7)
70+ years	220	77.4 (71.6, 130.5)	13.6 (–)	67.3 (64.2, 69.3)	158.5 (133.5, 233.5)
Sex					
Male	892	91.4 (73.1, 1295.5)	13.6 (–)	64.9 (62.8, 74.7)	183.9 (148, 1372.8)
Female	863	120 (77.9, 1301.7)	13.6 (–)	70.8 (65.3, 103.3)	224.3 (156.1, 1384.3)

[a]As each participant was assigned the same Wi-Fi-router exposure, all participants receive the same dose estimate in this category, as such IQR is not shown.

device use functions as desired with accompanying output powers and use durations allows for detailed dose estimations: rather than a single whole-day average, many use cases and situations can be included. Detailed input information must be available; however, either from interviews, questionnaires or monitoring apps concerning mobile device use. The three main factors in dose estimation, SAR, output power and duration of use, each introduced uncertainties in the model,

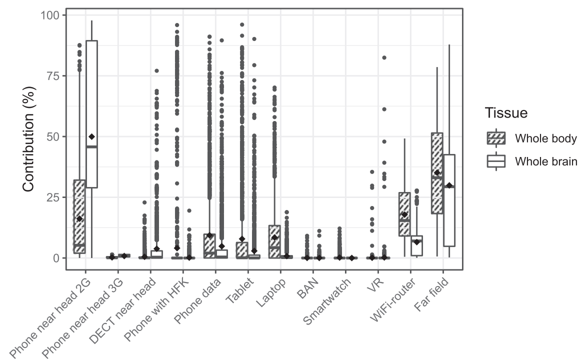

Fig. 1 Relative contribution of sources to total dose of whole-body and whole-brain (HFK hands-free kit, BAN body area network, VR virtual reality headset). Percentile distribution is shown using boxplots, and means are indicated with a diamond marker.

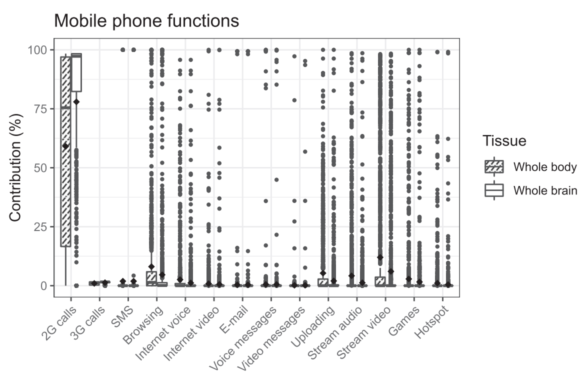

Fig. 2 Relative contribution of mobile phone functions to total dose of whole-body and whole-brain. Percentile distribution is shown using box-whiskerplots, and means are indicated with a diamond marker.

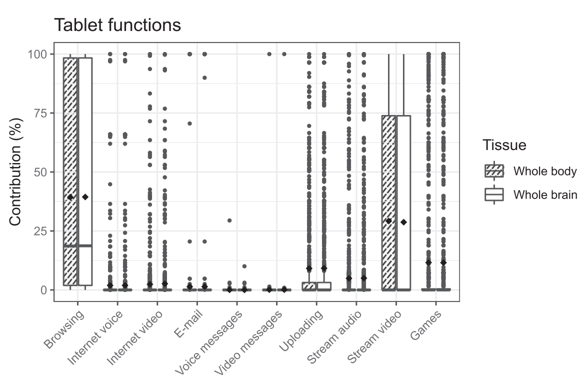

Fig. 3 Relative contribution of tablet functions to total dose of whole-body and whole-brain. Percentile distribution is shown using boxplots, and means are indicated with a diamond marker.

leading to a large global uncertainty on an individual level. For SAR estimations uncertainty in both model input parameters and interpolation methods used will propagate through the transfer algorithm [9]. Estimating the output power proved to be difficult. The total dose strongly depends on the output power strength of the source, and output power is dependent on many factors including current use and reception quality. Little information on output power is available in existing literature, therefore we had to depend largely on expert opinions. As output power is an important factor in estimating the dose, an under- or overestimation might strongly influence the results. This reasoning also applies to durations of use, where an under- or overestimation of actual use time might do the same. Concerning the survey, the response rate was relatively low: 1755 responses (4.4%) out of 40,000 invitations. This could be a result of the recruitment method in which a large selection of households was sent an invitational letter without previous contact or media attention. The low response rate may limit the generalisability of the results. There were differences in the age distribution between the four participating countries, with the participants from France being the oldest and Spain having mostly younger participants. The age differences may have influenced the difference between countries. Despite these drawbacks, the survey is the most detailed source of information available on the use of modern communication devices to date.

Dose estimations

Two previous publications [7, 8] described a similar dose integration model for estimating RF-EMF dose. The model of Roser et al. includes near-field sources in the form of mobile and DECT phones, laptops and tablets as well as far-field sources. The mean whole-body (339.9 mJ/kg/day) and mean whole-brain (1559.7 mJ/kg/day) doses found by Roser et al. were higher than our mean findings (290.4 and 801.5 mJ/kg/day, respectively). The main difference between mean whole-brain doses is driven by higher near-field dose in Roser et al., particularly GSM900/GSM1800 mobile phone calls made near the head. This could be explained by the fact that we found an average duration of nearly 10 min for 2G and 3G phone calls combined versus the 17.2 min used by Roser et al. While not specified, different assumptions on network technology used (i.e. 2G versus 3G) could further influence estimations, as 3G technology uses lower output powers [20]. Conversely, our far-field estimations were higher, which can be traced back to the input data concerning far-field exposure: the time-weighted average exposures from the GERoNiMO measurements were higher than those used by Roser et al., which could be explained by increasing use of RF-EMF in society over the years, with the GERoNiMO measurements being more recent (September 2014 to February 2016 versus June 2012 to March 2013). Compared to Lauer et al., the estimated far-field dose is very similar, with Lauer et al. defining three exposed groups with far-field dose results ranging from 35.2 to 73.5 mJ/kg/day for the whole-body, while we observed a median dose of 56.4 mJ/kg/day. The advantages of our model over these previous models are the ability to: include multiple use cases each with their own related output power and position relative to the body (i.e. the scenarios of use); to include new technologies, devices and uses as they are deployed; and to estimate dose for many more anatomical sites.

Relative contributions per source

For the whole-brain the use of mobile phones near the head remains by far the main contributor to total dose. Phone calls performed on a 2G network, which generally uses a higher output power, provide a high contribution followed at a distance by nearby Wi-Fi-routers. Regarding whole-body dose, the contribution of other sources becomes more important. Far-field exposure, Wi-Fi-routers, laptops, tablets and even other functions than calling on a mobile phone provide a higher contribution to the whole-body dose. This indicates that while just looking at mobile phone calls may include most RF-EMF exposure for health outcomes focused on the brain, this is not the case for the whole-body. In addition, adaptive output power control depending on the mobile phones' function may further influence exposure levels, as explained below. When looking at potential health endpoints at anatomical sites other than the brain (e.g. heart, liver), multiple devices should be included.

RF-EMF dose reduction

With the relative contributions found in this study, various non-technical interventions may be considered to reduce overall RF-EMF dose. The avoidance of using a mobile phone near the head when using 2G networks may be an efficient way to reduce overall exposure by half for the whole-brain and up to 25% for the whole-body. This can be achieved on modern smartphones by disabling the use of 2G networks altogether or by using a wired hands-free kit instead. In the latter case, the exposure will shift from the head to other parts of the body when the device is held in a hand or pocket. In general, we observed a higher RF-EMF dose with device functions that require higher amounts of data, such as video streaming. Placing the device on a nearby surface or stand with data intensive uses can be considered to reduce dose. For far-field exposure, it is generally difficult to achieve individual reduction as these are continuous exposures generally not controlled by the subject, such as FM radio broadcast and mobile phone antennas.

Conclusion

In conclusion, we developed the most comprehensive RF-EMF dose estimation tool to date. Realistic population exposure scenarios were obtained by using data on mobile phone use from an international survey in the model. Overall RF-EMF dose for the whole-body and whole-brain was found to be higher in younger age groups in comparison with older groups. Mobile phone calls on 2G networks were found to be the main contributor to whole-brain RF-EMF dose. For whole-body dose, far-field of telecommunications and multiple other RF-EMF sources played a prominent role as well. These findings can be used in the creation of non-technical interventions aimed at lowering RF-EMF exposure from current technologies, with the modular structure of the model allowing inclusion of new technologies such as 5th generation networks. Future epidemiological studies involving RF-EMF exposure should take multiple RF-EMF sources into account by adding detailed questions on exposure duration when investigating other anatomical sites than the brain.

Code availability

The model is available upon request: R.C.H.Vermeulen@uu.nl. Version 1.2.6 was used to generate the results presented here.

Funding This project was funded by the European Union's FP7 programme within the framework of the international project GERoNiMO ('Generalized EMF Research using Novel Methods—an integrated approach: from research to risk assessment and support to risk management', GA603794, 01/2014–12/2018) and by ANSES—the French Agence nationale de sécurité sanitaire de l'alimentation, de l'environment et du travail—within the CREST project ('Characterization of exposure to radio-frequency (RF) induced by new uses and technologies of mobile communication systems', 2013–2017). This project also received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant agreement No. 665501 with the research Foundation Flanders (FWO). Arno Thielens is an FWO [PEGASUS]² Marie Skłodowska-Curie fellow. ISGlobal is a member of the CERCA Programme, Generalitat de Catalunya.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

1. World Health Organization. WHO research agenda for radiofrequency fields. WHO Libr. Cat. Data. 2010; p. 42.
2. Röösli M, Lagorio S, Schoemaker MJ, Schüz J, Feychting M. Brain and salivary gland tumors and mobile phone use: evaluating the evidence from various epidemiological study designs. Annu Rev Public Health. 2019. https://doi.org/10.1146/annurev-publhealth-040218-044037.
3. Cardis E, Richardson L, Deltour I, Armstrong B, Feychting M, Johansen C, et al. The INTERPHONE study: design, epidemiological

methods, and description of the study population. Eur J Epidemiol. 2007. https://doi.org/10.1007/s10654-007-9152-z.
4. Bürgi A, Frei P, Theis G, Mohler E, Braun-Fahrländer C, Fröhlich J, et al. A model for radiofrequency electromagnetic field predictions at outdoor and indoor locations in the context of epidemiological research. Bioelectromagnetics. 2010;31:226–36.
5. Varsier N, Plets D, Corre Y, Vermeeren G, Joseph W, Aerts S, et al. A novel method to assess human population exposure induced by a wireless cellular network. Bioelectromagnetics. 2015. https://doi.org/10.1002/bem.21928.
6. Aerts S, Wiart J, Martens L, Joseph W. Assessment of long-term spatio-temporal radiofrequency electromagnetic field exposure. Environ Res. 2018. https://doi.org/10.1016/j.envres.2017.11.003.
7. Roser K, Schoeni A, Bürgi A, Röösli M. Development of an RF-EMF exposure surrogate for epidemiologic research. Int J Environ Res Public Health. 2015;12:5634–56.
8. Lauer O, Frei P, Gosselin MC, Joseph W, Röösli M, Fröhlich J. Combining near- and far-field exposure for an organ-specific and whole-body RF-EMF proxy for epidemiological research: a reference case. Bioelectromagnetics. 2013;34:366–74.
9. Liorni I, Capstick M, van Wel L, Wiart J, Joseph W, Cardis E, et al. Evaluation of specific absorption rate in the far-field, near-to-far field and near-field regions for integrative radiofrequency exposure assessment. Radiat Prot Dosimetry. 2020. https://doi.org/10.1093/rpd/ncaa127.
10. CREST. Characterization of exposure to radio-frequency (RF) induced by new uses and technologies of mobile communication systems. 2013. http://radiation.isglobal.org/crest.
11. Joseph W, Pareit D, Vermeeren G, Naudts D, Verloock L, Martens L, et al. Determination of the duty cycle of WLAN for realistic radio frequency electromagnetic field exposure assessment. Prog Biophys Mol Biol. 2013. https://doi.org/10.1016/j.pbiomolbio.2012.10.002.
12. Slottje P, Yzermans CJ, Korevaar JC, Hooiveld M, Vermeulen RCH. The population-based occupational and environmental health prospective cohort study (AMIGO) in the Netherlands. BMJ Open. 2015. https://doi.org/10.1136/bmjopen-2014-005858.
13. Eeftens M, Struchen B, Birks LE, Cardis E, Estarlich M, Fernandez MF, et al. Personal exposure to radio-frequency electromagnetic fields in Europe: is there a generation gap? Environ Int. 2018;121:216–26.
14. CBS Statistics Netherlands. CBS Statistics Netherlands. 2017. https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81565NED/table?ts=1538661827972. Accessed 4 Oct 2018.
15. Statistik B für. Schweizerische Eidgenossenschaft Eidgenössisches Departement des Inneren EDI. 2012.
16. Eurobarometer S Health and food. Spec. Barom. 246. 2006.
17. Goedhart G, van Wel L, Langer CE, de Llobet Viladoms P, Wiart J, Hours M, et al. Recall of mobile phone usage and laterality in young people: the multinational Mobi-Expo study. Environ Res. 2018. https://doi.org/10.1016/j.envres.2018.04.018.
18. Berman D, Crump K. Final draft: technical support document for a protocol to assess asbestos-related risk. Report no. 9345.4-06. Washington, DC: U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response; 2003.
19. R Core Team. R: a language and environment for statistical computing. R Foundation for Statistical Computing. 2013. http://www.r-project.org/.
20. Kühn S, Kuster N. Field evaluation of the human exposure from multiband, multisystem mobile phones. IEEE Trans Electromagn Compat. 2013;55:275–87.