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Radiofrequency electromagnetic fields from mobile communication: Description of modeled dose in brain regions and the body in European children and adolescents

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ABSTRACT

Background: Little is known about radiofrequency electromagnetic fields (RF) from mobile technology and resulting dose in young people. We describe modeled integrated RF dose in European children and adolescents combining own mobile device use and surrounding sources.

Methods: Using an integrated RF model, we estimated the daily RF dose in the brain (whole-brain, cerebellum, frontal lobe, midbrain, occipital lobe, parietal lobe, temporal lobes) and the whole-body in 8358 children (ages 8–12) and adolescents (ages 14–18) from the Netherlands, Spain, and Switzerland during 2012–2016. The integrated model estimated RF dose from near-field sources (digital enhanced communication technology (DECT) phone, mobile phone, tablet, and laptop) and far-field sources (mobile phone base stations via 3D-radiowave modeling or RF measurements).

Results: Adolescents were more frequent mobile phone users and experienced higher modeled RF doses in the whole-brain (median 330.4 mJ/kg/day) compared to children (median 81.8 mJ/kg/day). Children spent more time using tablets or laptops compared to adolescents, resulting in higher RF doses in the whole-body (median whole-body dose of 81.8 mJ/kg/day) compared to adolescents (41.9 mJ/kg/day). Among brain regions, temporal lobes received the highest RF dose (medians of 274.9 and 1786.5 mJ/kg/day in children and adolescents,

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respectively) followed by the frontal lobe. In most children and adolescents, calling on 2G networks was the main contributor to RF dose in the whole-brain (medians of 31.1 and 273.7 mJ/kg/day, respectively).
Conclusion: This first large study of RF dose to the brain and body of children and adolescents shows that mobile phone calls on 2G networks are the main determinants of brain dose, especially in temporal and frontal lobes, whereas whole-body doses were mostly determined by tablet and laptop use. The modeling of RF doses provides valuable input to epidemiological research and to potential risk management regarding RF exposure in young people.

1. Introduction

Over the past thirty years, mobile communication technology has transformed society, providing new platforms for near-constant communication, media and entertainment consumption, and socializing. This means that children today will experience more radiofrequency electromagnetic fields (RF) exposure in childhood and a higher accumulated lifetime exposure, compared to previous generations (Markov and Grigoriev 2015; Rosenberg 2013; Otto and von Mühlendahl, 2007). There is concern that elevated exposure to RF at a young age, while organs are rapidly developing, could lead to adverse health effects in childhood or later in life (Rice and Barone 2000; Feychting 2011; Kheifets et al., 2005; Schüz 2005). Epidemiological research has yet to comprehensively describe these recent levels of RF exposure in young populations, which is necessary for understanding its possible long- and short-term health effects. Therefore, a clearer understanding of RF exposure, specifically in children and adolescents, is urgently needed during this new era in mobile communication.

Epidemiological studies estimating children's RF exposure have been rare, and the recent studies that have attempted to describe RF exposure in children have their limitations. For example, epidemiological studies that estimated exposure based solely on mobile phone use (Sudan et al., 2016; Abramson et al., 2009) or solely on geospatial modeling (Beekhuizen et al., 2013; Schoeni et al., 2016) do not account for RF doses from far- and near-field sources together. In studies that accounted for far- and near-field sources together, measurements could not account for the differences in RF exposure from different types of device use activities (such as calling, texting, internet browsing, or video streaming) or network coverage (2G, 3G, or WiFi), factors which effect device output power, and thus RF dose received (Huss et al., 2015; Guxens et al., 2016). Alternatively, studies measuring personal RF exposure are sometimes in small populations ($n < 1000$), as they are labor intensive, and are unable to account for dose to specific tissues of the body, as measured values depend highly on the distance between the emitting source and the measurement device, which is not necessarily the same as the distance between the emitting source and the body (Birks et al., 2018; Roser et al., 2017; Calvente et al., 2015; Thomas et al, 2008, 2009, 2010bib_Thomas_et_al_2010bib_Thomas_et_al_2009bib_Thomas_et_al_2008).

A recent study in Switzerland used dose models which integrated near- and far-field estimates, types of device use activities, and network coverage to estimate RF dose to the whole-brain, the brain's gray matter, and the whole-body (Lauer et al., 2013; Roser et al., 2015). However, these analyses did not model dose in specific regions of the brain and were limited to small samples (Schoeni, Roser, and Röösli 2015, 2017bib_Schoeni_et_al_2015; Foerster et al., 2018bib_Schoeni_et_al_2017). Therefore, further estimates of modeled RF dose in specific regions of the brain in larger populations are necessary.

This study aims to model RF dose in 7 regions of the brain and whole-body, describe this modeled dose and the mobile device use habits contributing to it, in two age groups from a large sample of children (ages 8–12) and adolescents (ages 14–18) across three European countries between 2012 and 2016. This work combines existing data from four population based cohort studies, resulting in the largest epidemiological RF dose description of children's brains and bodies to date.

2. Methods

2.1. Study design and population

As part of the Generalized EMF Research using Novel Methods (GERoNiMO) Project (http://radiation.isglobal.org/geronimo) and the Radiofrequency electromagnetic fields exposure and brain development (REMBRANDT) Project (http://radiation.isglobal.org/index.php/nl/radiation-programme-projects/2018-06-19-08-32-04/rembrandt), four population-based prospective cohorts spanning Europe (Table 1) were combined for analysis regarding mobile device use at ages 8–18. These were: the Dutch Amsterdam Born Children and their Development Study (ABCD) (Eijsden et al., 2011), the Dutch Generation R Study (Generation R) (Kooijman et al., 2016), Switzerland's Health Effects Related to Mobile phonE use in adolescentS (HERMES) (Schoeni et al. 2015), and the Spanish Environment and Childhood Project (INMA) (Guxens et al., 2012). Adolescents in HERMES were recruited for a one year follow-up study with two data collection periods: at baseline and one year later. In this analysis, we used HERMES data collected at baseline. The Spanish INMA cohort consisted of several regional subcohorts, comprising of Gipuzkoa, Sabadell, Valencia, (collectively referred to as INMA young) and Menorca (referred to as INMA Menorca). Enrollment in the ABCD, Generation R, and INMA occurred during the mother's pregnancy, spanning years 1996–2008; while adolescents in the HERMES cohort were recruited at ages 13–14 between 2012 and 2014. In all cohorts, informed consent was obtained from all participants' parents or guardians in accordance with each center's institutional review board or ethics committee. Data regarding mobile device use was collected at different ages during 2012–2016, depending on the cohort (Table 1). Across all cohorts, 8358 participants met our inclusion criteria of having information on mobile device use and proximity to mobile phone base stations at ages 8–18. Excluded participants that were missing this information were either lost to follow-up or had incomplete questionnaires. Based on time of data collection for this analysis, cohorts were grouped into two age groups: children (ABCD, Generation R, and INMA young) and adolescents (HERMES and INMA Menorca).

2.2. Exposure to RF sources and modeling of RF dose to brain and body

2.2.1. Use of mobile communication devices

In ABCD, Generation R, and INMA young cohorts, parents were asked via questionnaire to estimate children's frequency and duration of mobile device use when children were 8–12 years old. Adolescents from the HERMES and INMA Menorca reported this information themselves via questionnaire (Table 1) when they were 14 and 18 years old, respectively. The following variables were collected regarding use (yes/no) and average daily or weekly duration of use: Digital Enhanced Cordless Telecommunications (DECT) calls, mobile phone calls, mobile phone internet browsing, mobile phone emailing, laptop use, tablet use, and laptop or tablet connection to internet. Questionnaires asked for number of text messages or app-based messages sent. Questionnaires also asked for model of mobile phone (smartphone, bar, slide, or flip), except in ABCD. In HERMES, adolescents were asked to report "daily data traffic" on mobile phone instead of browsing or emailing, which we have reported as mobile phone internet browsing. HERMES adolescents were also asked to report tablet and laptop use together, which we have reported as tablet use. In HERMES and INMA Menorca, adolescents were asked to report laterality (left or right) of mobile phone use, and use of Bluetooth or other hands-free device during mobile phone calls. For questionnaires, see supplemental materials (Supplementary Table S1).

2.2.2. Far-field RF from mobile phone base stations in the home

For most participants, daily RF exposure in the home from nearby mobile phone base stations was estimated using a three-dimensional radiowave propagation model, NISMap. NISMap models estimated RF exposure from base stations emitting the following downlink frequencies: 800 MHz (in INMA young and INMA Menorca only), 900 MHz, 1800 MHz, and 2100 MHz. Based on geocoding of the participant's home address and the floor level of the participant's bedroom, NISMap estimated RF exposure in power density (mW/m^2), considering the three dimensional environment by including topography and detailed information about nearby mobile phone base stations (such as output power, height above ground and direction) (Bürgi et al., 2010). Information regarding characteristics of the participant's bedroom was collected via questionnaires along with device use details. For questionnaires, see Supplementary Table S1. In HERMES, additional daily exposure at school from mobile phone base stations was modeled with NISMap based on the adolescent's geocoded school address.

2.2.3. Far-field RF from other sources in all microenvironments

To estimate far-field exposure from other sources (such as FM, TV, uplink, DECT, and WiFi sources) in all microenvironments, estimates were made using personal RF exposimeter measurements taken over up to 72 h in a previous study in a subset of cohort participants in all regions (Birks et al., 2018; Eeftens et al., 2018) (Supplementary Table S2). From this point on, we will refer to these measurements as exposimeter estimates. Exposimeter estimates from the previous study and time spent in each microenvironment (home, school, outdoors, traveling) were averaged for each microenvironment and frequency band and matched by regional cohort. However, the Generation R cohort was not part of this previous study, therefore exposimeter measurements taken in ABCD were used for estimates in both ABCD and Generation R, given the similarities in infrastructure and population density of the studies' centers: Amsterdam and Rotterdam. For a description of exposimeter estimates, please see Supplementary Table S3.

For 114 children in INMA young and 21 adolescents in INMA Menorca, it was not possible to geocode home addresses to use for NISMap calculations. For this reason, regional medians of exposimeter estimates were used to estimate far-field RF exposure from mobile base stations in the home (Supplementary Table S2). For far-field RF estimates used in the home, see Supplementary Table S3.

2.2.4. Integrated model of RF dose in the brain and body

To model RF dose in specific regions and tissues of the brain and body, Liorni et al., (2020) developed an integrated dose model to include many relevant RF sources, based on specific absorption rate (SAR) transfer approximations developed and applied in van Wel et al., in 2018 (van Wel et al., 2020) on the basis of the data collected within the Characterization of exposure to RF induced by new uses and technologies of mobile communication systems (CREST) project (https://www.isglobal.org/en/-/crest) and the previously mentioned GERoNiMO project. This integrated model estimates the exposure to RF systems in the near-field and far-field, allowing for a broad exposure assessment. The model takes into account source specific attributes (source type, output power, operating frequency), personal characteristics (body mass, weight), and the specific exposure scenario (position relative to the body, type of use, duration of use), allowing for better dose estimation and insight in the contribution of different sources and uses to the total RF dose received (Cabré-Riera et al., 2020a).

SAR approximations were derived on the basis of a large-scale numerical study analysing the exposure of the human anatomical phantom belonging to the Virtual Population (Gosselin et al., 2014) developed by the IT'IS Foundation (https://itis.swiss) to different RF systems in several exposure scenarios. Virtual population phantoms were assigned to participants based on age and mass of the participant (Supplementary Table S4). SAR values were transformed to dose values by multiplying the SAR by output power of the device then by relevant exposure durations. The average output power of these devices was derived from the literature and expert opinion (Persson et al., 2012; Joseph et al., 2013). Output powers for device use specific to device, network, and activity can be found in Supplementary Table S5.

RF dose in 7 brain regions (whole-brain, cerebellum, frontal lobe, midbrain, parietal lobe, occipital lobe, and temporal lobes) and the whole-body was calculated by summing contributions of all near- and far-field exposure scenarios, resulting in region-specific doses in mJ/kg/day (Supplementary Table S6). The model calculated the integrative dose from all sources combined and the relative contribution of each source. For a summary of assumptions or estimates used in exposure modeling, we refer to Supplementary Methods S1 and Table S7.

2.3. Sociodemographic factors

Sociodemographic factors were collected in all cohorts via questionnaires during follow-up or at baseline (Table 2). As few previous studies have investigated sociodemographic factors and potential associations with mobile device use and RF exposure (Langer et al., 2017; Birks et al., 2018; Andone et al., 2016), we considered sociodemographic factors in our analyses to further explore possible associations. Characteristics of children such as age and sex and characteristics of mothers such as age at birth, marital status (living with a partner or living alone), education (highest level completed: primary, secondary, university or higher), and parity (0 children, 1 child, >1 child) were considered.

Table 1
Description of cohorts in analysis.

	Cohort	Location	Enrollment		Data collection of mobile device use			
			Time period	N	Mean age	Reporter	Time period	N
Children	ABCD	Amsterdam, NL	2003–2004	8266	12 y	parent	2015–2016	2593
	Generation R	Rotterdam, NL	2002–2006	9901	10 y	parent	2015–2016	3304
	INMA young	Gipuzkoa, Sabadell, and Valencia, ES	2003–2008	2271	8-10 y	parent	2014–2016	1311
	HERMES	Switzerland, CH	2012–2014	892	14 y	self	2012–2014	892
Adolescents	INMA Menorca	Menorca, ES	1997–1998	482	18 y	self	2015–2016	258
				25,732				8358

Abbreviations: ABCD, Amsterdam Born Children and their Development; CH, Switzerland; ES, Spain; HERMES, Health Effects Related to Mobile phonE use in adolescentS; INMA, Spanish Childhood and Environment Project; NL, the Netherlands; y, years.

Table 2
Sociodemographic factors and device use by cohort.

	Overall	Children (ages 8–12)			Adolescents (14–18)	
		ABCD	Generation R	INMA young	HERMES	INMA Menorca
	(n = 8358)	(n = 2593)	(n = 3304)	(n = 1311)	(n = 892)	(n = 258)
Sociodemographic factors						
Age (mean years (SD))	11.0 (2.1)	12.0 (0.2)	9.7 (0.3)	8.7 (0.7)	14.0 (0.9)	17.6 (0.2)
Female (vs male) (%)	50.9	50.3	50.7	49.1	56.1	52.0
Age of mother at birth (mean years, SD)	31.7 (4.5)	32.3 (4.2)	31.1 (4.8)	32.1 (3.9)	29.4 (4.1)	30.2 (4.6)
Marital status of mother (% living with partner vs living alone)	88.1	81.5	88.6	99.7	85.3	100.0
Highest level of maternal education (% university or higher)	54.6	75.3	53.5	38.6	32.6	16.4
Parity (% >2 children vs ≤ 2)[a]	13.8	8.8	11.5	6.0	49.2	8.6
Device use habits						
DECT home phone (% yes vs no)	80.2	83.4	79.8	68.8	91.7	71.6
daily median minutes (min-max)	0.4 (0–100)	0.3 (0–100)	0.3 (0–90)	0.0 (0–57)	2.5 (0–61)	0.1 (0–180)
Use of mobile phone (% yes vs no)	60.0	82.0	49.9	9.8	95.3	99.2
daily median call minutes (min-max)	0.7 (0–300)	0.7 (0–180)	0.4 (0–180)	0.0 (0–80)	6.4 (0–300)	1.4 (0–180)
Texting (% yes vs no)	63.2	77.2	53.0	31.9	95.3	99.2
daily median n of texts (min-max)	0.4 (0–1200)	1.4 (0–400)	0.1 (0–500)	0.0 (0–30)	30.5 (0–62)	72.5 (0–1200)
Browsing (% yes vs no)	59.6	76.7	54.2	23.6	75.5	83.9
daily median minutes (min-max)	2.1 (0–360)	12.9 (0–360)	0.0 (0–360)	0.0 (0–90)	53.6 (0–116)	15.0 (0–360)
Emailing (% yes vs no)	15.1	15.9	14.1	4.4	–	72.1
daily median minutes (min-max)	0.0 (0–400)	0.0 (0–120)	0.0 (0–120)	0.0 (0–60)	–	4.3 (0–400)
Use of laptop (% yes vs no)	87.5	93.0	89.1	70.8	–	65.2
connected to internet (% yes vs no)[b]	90.8	95.1	91.2	81.8	–	72.1
daily median minutes (min-max)	19.1 (0–514)	24.7 (0–376)	18.9 (0–423)	8.6 (0–223)	–	30.0 (0–514)
Use of tablet (% yes vs no)	77.9	94.0	89.6	67.8	27.3	51.7
connected to internet (% yes vs no)[b]	89.7	95.7	90.3	73.8	98.4	60.0
daily median minutes (min-max)	24.3 (0–635)	30.4 (0–442)	30.0 (0–635)	12.1 (0–231)	0.0 (0–350)	6.1 (0–90)

Abbreviations: ABCD, Amsterdam Born Children and their Development; DECT, digital enhanced cordless telecommunications; HERMES, Health Effects Related to Mobile phonE use in adolescentS; INMA, Spanish Childhood and Environment Project.
- In HERMES, emailing on mobile phone was not collected. Participants reported laptop and tablet use together, we have reported it as tablet use.
[a] In HERMES, parity was not collected, children reported number of siblings instead.
[b] Among children that use device.

2.4. Statistical analysis

Among participants with at least one variable available on mobile device use (n = 8358), we performed multiple imputation of missing participant characteristics and duration of device use values using chained equations where 25 completed datasets were generated and analyzed using the standard combination rules for multiple imputation (Graham et al. 2007; Sterne et al., 2009). Distributions in the imputed datasets were very similar to those in the original data set (data not shown).

The integrated dose model could not be applied to imputed datasets. Therefore, missing values necessary for use of the RF dose model (sex, age, height, weight, duration of device activities, proportion of right/left use in HERMES and INMA Menorca, proportion of 2G/3G use in HERMES) were replaced using the mean value for the individual of those variables from the 25 imputed datasets per cohort (Supplementary Table S7). These datasets were used for calculation of the dose in the model.

Daily median device use durations, individual characteristics, and sociodemographic factors were described by cohort. Total daily median RF dose (mJ/kg) was modeled and described in each cohort for the whole-brain, cerebellum, frontal lobe, midbrain, occipital lobe, parietal lobe, temporal lobes, and the whole-body. Median modeled dose was described for relevant brain regions with respect to the following specific RF sources: all sources combined, DECT calls, 2G calls, 3G calls, mobile phone data use, laptops, tablets, and far-field.

Associations between sociodemographic factors with log-transformed RF dose to the whole-brain and whole-body were estimated using mixed models with random cohort effects. Cohort random effects allowed models to capture age effects and other exposure-releveant factors that are clustered per cohort. Geometric mean ratios and 95% confidence intervals were calculated. Models for the association between sociodemographic factors and log-transformed RF dose were adjusted for sex but not for age, given the high correlation between age and cohort.

All analyses were performed using Stata 14 statistical software (Stata Corporation, College Station, Texas) and R statistical software (R Core Team, 2013). Data from all cohorts was sent to and analyzed at ISGlobal in Barcelona, Spain.

3. Results

3.1. Children and adolescents' characteristics and device use habits

In children of ABCD (mean age 12 years), Generation R (10 years), and INMA young (9 years), the prevalence of any mobile phone use was 82%, 50%, and 10%, respectively. In HERMES (14 years) and INMA Menorca (18 years), adolescents were more prevalent mobile phone users with 95% and 99% reporting any use of a mobile phone, respectively (Table 2). While adolescents were more prevalent users of mobile phones than children, the type of use differed among cohorts. Adolescents in HERMES spent more time calling, with a daily median of 6 min for mobile phone and 3 min for DECT calls, while adolescents in INMA Menorca were more frequent users of text messaging or mobile app messaging (median of 73 messages per day). In child cohorts, however, these children spent more time using tablets than adolescents with ABCD, Generation R, and INMA young cohorts reporting median values of 30, 30, and 12 min per day, respectively. For a detailed description of device use in all cohorts, see Table 2.

3.2. Modeled daily RF dose in regions of the brain

Overall, modeled median RF dose in the whole-brain was 91.7 mJ/kg/day (Table 3), though this varied widely between cohorts and age

Table 3
Median modeled radiofrequency dose (mJ/kg/day) in brain regions and whole-body, overall, by age group, and by cohort.

	Overall	Children	Adolescents	ABCD	Generation R	INMA young	HERMES	INMA Menorca
N	8358	7208	1150	2593	3304	1311	892	258
whole-brain	91.7	83.7	330.4	98.9	85.3	52.6	451.9	107.1
cerebellum	46.1	38.4	219.0	40.8	76.0	6.4	297.7	56.4
frontal lobe	136.9	123.4	582.9	160.3	113.2	83.8	781.9	183.4
midbrain	53.9	48.9	246.0	52.1	53.4	27.7	340.2	63.6
occipital lobe	101.1	96.1	180.6	95.3	101.5	83.0	249.8	57.2
parietal lobe	85.7	82.2	147.9	83.1	83.6	74.5	186.5	51.8
temporal lobes	316.9	274.9	1786.5	343.5	306.5	125.3	2535.9	537.2
whole-body	76.9	81.8	41.9	87.2	82.0	67.2	37.9	56.7

Abbreviations: ABCD, Amsterdam Born Children and their Development; HERMES, Health Effects Related to Mobile phonE use in adolescentS; INMA, Spanish Childhood and Environment Project.

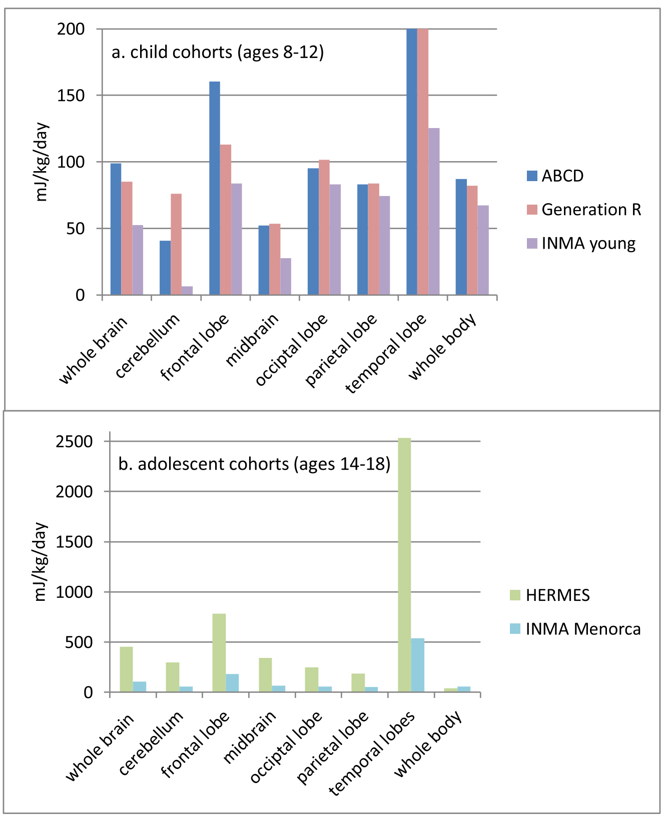

Fig. 1. Median daily RF dose (mJ/kg/day) in brain regions and whole-body. by cohort among **a)** child cohorts (smaller scale) and **b)** adolescent cohorts (larger scale).

groups (83.7 mJ/kg/day in children and 330.4 mJ/kg/day in adolescents) (Supplementary Fig. S1a). Models estimated that temporal lobes received more RF than other brain regions (medians 274.9 and 1786.5 mJ/kg/day in children and adolescents, respectively), followed by the frontal lobe (123.4 and 582.9 mJ/kg/day in children and adolescents, respectively) (Fig. 1a and b). In children, most other regions, including the cerebellum, the midbrain, the occipital lobe, and the parietal lobe received a dose of less than 102 mJ/kg/day, while in adolescents these brain regions received a dose of less than 300 mJ/kg/day.

3.3. Contributions by RF sources to modeled daily RF dose in regions of the brain

Contributors to modeled daily RF dose in the brain varied by age groups due to different habits of device use. In children, modeled dose in the whole-brain was comprised of RF from 2G (31.1 mJ/kg/day), far-field (8.5 mJ/kg/day) and tablet use (6.7 mJ/kg/day), with dose in the temporal lobes dominated by 2G calls. These results were mainly driven by ABCD and Generation R, since among the INMA young children, whole-brain dose was mostly comprised of exposure from far-field (10.5 mJ/kg/day) exposure. Modeled dose in the whole-brain, frontal and temporal lobes in adolescents overwhelmingly originated from mobile phone calls on 2G networks (median 2G dose was 273.7 mJ/kg/day for the whole-brain and 1595.9 mJ/kg/day for the temporal lobe) (Supplementary Table S8) (Fig. 2a–c). The remaining dose in the brains of adolescents was very low and mostly comprised of RF from 3G (7.3 mJ/kg/day), DECT (6.1 mJ/kg/day), farifield (5.9 mJ/kg/day), and mobile phone data (0.5 mJ/kg/day).

3.4. Modeled daily RF dose and its contributors in the whole-body

Daily median whole-body dose in children (81.8 mJ/kg) resulted mainly from tablet use (31.2 mJ/kg/day) (Table 3). Meanwhile, median daily whole-body dose in adolescents (41.9 mJ/kg) resulted mainly from 2G and far-field exposure (5.2 and 4.7 mJ/kg/day, respectively), though this varied between adolescent cohorts (Fig. 2d).

3.5. Sociodemographic characteristics and RF dose

Older children (per year of age) and females experienced higher modeled RF dose in the whole-brain (Supplementary Table S9). Children of less educated mothers and of mothers that lived alone received more RF dose in the whole-brain. Children of younger mothers had slightly higher RF dose in the brain. Whole-body RF dose was higher in males and children or adolescents of mothers that were more educated (Supplementary Table S9).

4. Discussion

In this study, we modeled daily RF dose in 7 brain regions and the whole-body in children and adolescents from four European prospective cohorts, based on parent- or self-reported mobile device use and modeled or measured exposure to far-field RF sources. Adolescents were more prevalent mobile phone users, and therefore experienced much higher RF dose to the brain than children. Children spent relatively more time using tablets or laptops than calling, and experienced higher RF dose to the whole-body compared to adolescents. Both children and adolescents received the highest RF dose in the temporal and frontal lobes of the brain. Mobile phone calling on 2G networks was the main contributor to frontal and temporal lobe dose in both age groups, followed by far-field exposure in children, and followed by calling on 3G or DECT networks in adolescents.

This is the first study to quantify modeled RF dose in the whole-body and specific regions of the brain (whole-brain, cerebellum, frontal lobe, midbrain, parietal lobe, occipital lobe, and temporal lobes) in children and adolescents and to describe how this dose differs with RF sources. Previous modeling of RF dose in the whole-brain in adolescents has been done in Switzerland in the HERMES cohort. In 2015, Roser et al.

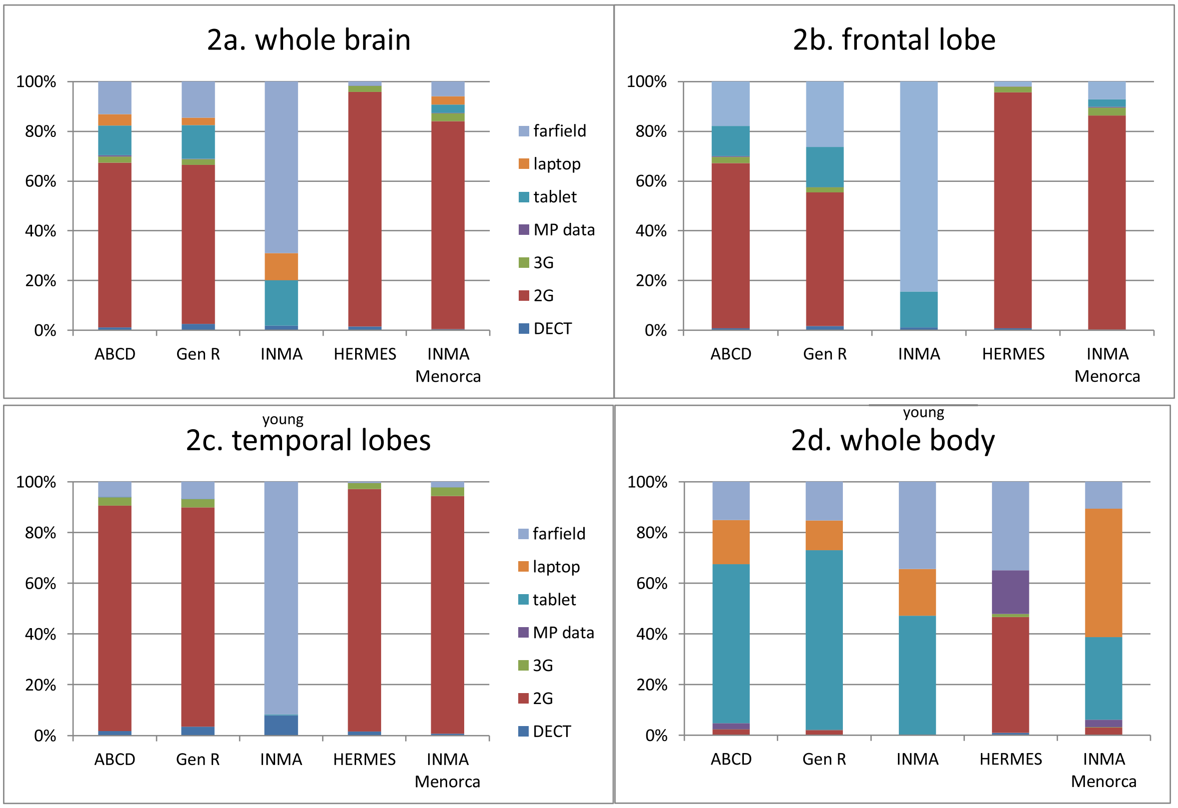

Fig. 2. Relative median dose contributions (%) by RF source in the following regions: **a)** whole-brain, **b)** frontal lobe, **c)** temporal lobes, and **d)** whole-body.

estimated mean RF doses in the whole-brain (1559.7 mJ/kg/day) in a sample of 400+ adolescents (Roser et al., 2015). Alternatively, Foerster et al. (2018) used average reported device use values over one year (at baseline and follow-up) to apply an exposure estimate model to a HERMES sample (n = 676) and estimated mean RF dose in the whole-brain (858 mJ/kg/day) (Foerster et al., 2018). For both of those analyses, RF dose estimates were higher than means in our analysis of HERMES (data not shown). This is likely due to differences in assumptions in the exposure model. For example, Foerster et al. accounted for mobile phone data traffic use on mobile phone networks, where as our calculations assumed mobile phone data use on WiFi networks. Foerster et al. also accounted for daily duration of carrying the mobile phone near the body, an exposure scenario not accounted for in our analysis as this variable was not available in all cohorts.

Children's and adolescents' temporal lobes and frontal lobes received more RF dose than all other regions of the brain. This makes sense considering where the mobile phone is held (next to the ear or in front of the face) and where tablets are held (in front of the face). The frontal lobe is important for various higher-order cognitive functions, such as managing emotions, attentional control, abstract thinking, among others (Rosso et al., 2004; Baars and Gage 2010). Meanwhile, functions of the temporal lobes are involved with creating and storing new memories, language recognition, among others (Baars and Gage 2010). Previous epidemiological studies evaluating the association between RF dose in the brain and neurodevelopmental outcomes in children are few and specific to HERMES adolescents in Switzerland (Schoeni et al. 2015; Foerster et al., 2018). In these studies, researchers found RF dose to the whole-brain was associated with decrease in figural memory performance. Further analysis of RF dose in the frontal and temporal lobes and cognitive function and behavioral outcomes is needed to evaluate the potential long- and short-term consequences of RF dose levels and neurocognitive development.

In children and adolescents who reported any mobile phone calling, 2G networks (including General Packet Radio Service (GPRS) or Enhanced Data rates for Global Evolution (EDGE) networks) contributed most to modeled daily RF dose in the whole-brain, frontal lobes, and temporal lobes. In our analysis, the proportion of 2G network usage was individually imputed for the HERMES cohort based on objective service provider data for n = 322, while for other cohorts, we used a country-wide average for all children based on a study completed (with objective data from a software application on individual mobile phones) around the same years that children reported device use (Langer et al., 2017; Goedhart et al., 2018). We must acknowledge that RF dose estimates for children and adolescents that made mobile phone calls could vary widely depending on 2G proportions used in the model. However, given the output power of a mobile phone while calling on a 2G network (89.7 mW) is 200 times that of that on a 3G network (0.45 mW), any proportion of calling on a 2G network would dominate RF exposure to the brain. Therefore, our modeled dose results demonstrate that RF dose to the brain could be greatly reduced by avoidance of mobile phone calls on 2G networks.

Generally, our results illustrate changing exposure as children mature and begin to use their own devices. We see that in child cohorts, especially the youngest (INMA Young), RF dose to the brain was very low and comprised of mostly far-field sources; while in older children and adolescents, RF dose was higher and dominated by 2G exposure from calling on their own devices. On a more granular level, we found that RF dose in the brain varied with child or adolescent characteristics and sociodemographic factors. Particularly, females, older children, children of mothers living alone, and children of mothers with less education were more prevalent mobile phone users and therefore experienced higher RF dose in the brain. Previous research has also demonstrated more prevalent mobile phone use in females and older children (Langer et al., 2017; Andone et al., 2016). Langer et al. demonstrated that adolescents whose mothers had less education made more frequent and longer mobile phone calls and used more mobile phone data (Langer et al., 2017), while Birks et al. illustrated that personal environmental RF was higher in children with less educated mothers (Birks et al., 2018). However, Langer's and Birks' analyses did not investigate mobile phone use or environmental RF and maternal marital status. Therefore, our findings add to current evidence pointing towards a complex relationship between mobile device use and sociodemographic factors.

While adolescents were more frequent users of mobile phones in our analysis, children were instead more frequent users of laptops or tablets. Estimates show this led to a higher RF dose in the whole-body in children than in adolescents. RF dose in the whole-body was higher in boys and children of mothers with more education. RF dose to the whole-body in small children has not yet been studied, to our knowledge, and its possible associations with health outcomes should be investigated in the future.

Our study has some important strengths, including its relatively large sample size and wide age range across three countries, and the harmonized and detailed information regarding mobile device use, individual characteristics, as well as sociodemographic factors. To date, this is the first study to model RF dose in specific regions (whole-brain, cerebellum, frontal lobe, midbrain, parietal lobe, occipital lobe, and temporal lobes) of the brain as a result of mobile device use and exposure to far-field RF sources together, in children and adolescents. To model this dose, we have used an integrated dose model, one of the most comprehensive RF dose estimation tools available in epidemiological research. Questionnaire data used for this modeling accounted for very detailed information regarding mobile device use. While previous studies may have estimated RF exposure based solely on mobile phone calls or proximity to nearby mobile phone base stations, our study was able to combine these exposure sources to model an integrated RF dose.

Our study also has several limitations. RF dose estimates are based on detailed modeling for which not all input data was available in our study population. Therefore in some cases, assumptions had to be made regarding several factors: laterality of mobile phone use, 2G/3G network use proportions, activities while using mobile phone data or laptops and tablets, WiFi data transfer rates (54 Mbps), time spent in certain microenvironments, and RF exposure from other far-field sources (Supplementary Methods S1 and Table S7). However, our exposure modeling was recently used by Calbré-Riera et al. and their sensitivity analyses explored additional higher-exposure and lower-exposure assumptions (Cabré-Riera et al., 2020b). Results demonstrated that changes in assumptions led to only marginal RF dose variations. Nevertheless, future epidemiological studies wishing to model RF dose should aim to collect as much information as possible on these factors in order to avoid these assumptions.

Additionally, previous research has found that adolescents and young people typically overestimate their duration of mobile phone calling, compared to objectively recorded measures (via software modified phones or service provider records) (Foerster et al., 2018; Langer et al., 2017). However, the self-reported estimates have been shown to accurately distinguish high-frequency users from low-frequency users (Langer et al., 2017). Regarding parents' estimation of child's device use, there are no studies validating parental reporting. Furthermore, there are no studies validating self or parental reporting of tablet or laptop use. It remains a possibility that parents under or overestimated tablet and laptop use, from which models estimated the most RF dose in the whole-body. However, in large scale population-based settings it would not be feasible to objectively monitor mobile phone, tablet, or laptop use. While estimating far-field exposures to RF, our modeling combined individual NISMap estimates with regional exposimeter measurements. While this method combines measurements with systematic differences, we felt it was important to try to capture many far-field exposures (as captured by exposimeter measurements) together with mobile phone base stations (as modleed by NISMap). Finally, the population included in this study was from population-based cohort studies. Some participants in these cohort studies were lost to follow-up or had incomplete questionnaires (no data was available regarding mobile device use) at ages 8–18, meaning they had to be excluded from analysis in this study. With this possibility for selection bias, our results may not represent the general population, limiting the external validity of our results (Szklo 1998).

5. Conclusion

Our study estimates for the first time in a large sample of children and adolescents RF dose in the whole-brain and whole-body, which regions of the brain receive the highest RF dose from mobile communication, and which sources and devices are the most relevant contributors in these age groups. Brain doses, especially those in the temporal and frontal lobes, were predominantly determined by mobile phone calls on 2G networks and less by other RF sources. The modeling of RF doses through use of an integrated dose model is a useful tool for future epidemiological research and potential risk management regarding RF exposure.

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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.2020.110505.

Conflict of interest

none declared

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