# Assessment of radiofrequency electromagnetic field exposure from personal measurements considering the body shadowing effect in Korean children and parents

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**Running heads:** Assessment of personal radiofrequency radiation exposure

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## ABSTRACT

We aimed to assess the personal radiofrequency electromagnetic field (RF-EMF) exposure levels of children and adults through their activities, with consideration to the body shadowing effect. We recruited 50 child-adult pairs, living in Seoul, Cheonan, and Ulsan, South Korea. RF-EMF measurements were performed between September and December 2016, using a portable exposure meter tailored to capture 14 Korean radiofrequency (RF) bands ranging from 87.5 to 5875 MHz. The participants carried the device for 48 hours and kept a time-activity diary using a smartphone application in flight mode. To enhance accuracy of the exposure assessment, the body shadowing effect was compensated during the statistical analysis with the measured RF-EMF exposure. The compensation was conducted using the hybrid model that represents the decrease of the exposure level due to the body shadowing effect. A generalized linear mixed model was used to compare the RF-EMF exposure levels by subjects and activities. The arithmetic (geometric) means of the total power density were 174.9 (36.6) μW/m$^2$ for all participants, 226.9 (44.6) for fathers, 245.4 (44.8) for mothers, and 116.2 (30.1) for children. By compensating for the body shadowing effect, the total RF-EMF exposure increased marginally, approximately 1.4 times. Each frequency band contribution to total RF-EMF exposure consisted of 76.7%, 2.4%, 9.9%, 5.0%, 3.3%, and 2.6% for downlink, uplink, WiFi, FM Radio, TV, and WiBro bands, respectively. Among the three regions, total RF-EMF exposure was highest in Seoul, and among the activities, it was highest in the metro, followed by foot/bicycle, bus/car, and outside. The contribution of base-station exposure to total RF-EMF exposure was the highest both in parents and children. Total and base-station RF-EMF exposure levels in Korea were higher than those reported in European countries.



**KEYWORDS:** Radiofrequency electromagnetic fields (RF-EMF), Portable exposure meter (PEM), Mobile phone base-station, Exposure assessment, Body shadowing effect.

## 1. Introduction

In recent years, with the rapid technological development of wireless communication, mobile phones have become increasingly popular. The number of mobile phone subscriptions per 100 people in 2016 was 101.5 worldwide, and 122.7 in South Korea (International Telecommunication Union, World Telecommunication/ICT indicators database).

Radio-frequency (RF) radiation usually refers to electromagnetic fields (EMF) in the frequency bands between 3 MHz and 300 GHz, and is emitted from radio and television (TV) broadcast antennas, Wireless-Fidelity (Wi-Fi) access points, routers, and clients (e.g. smart-phones, tablets), cordless and mobile phones, including their base-stations, and Bluetooth devices (Belyaev et al., 2016). An advanced exposure assessment for RF-EMF exposure, which has been lacking in previous epidemiological studies, is necessary to examine the causal relationship between RF-EMF exposure and adverse health effects (Wiedemann and Schutz, 2011).

Unlike ionizing radiation such as X-ray, RF-EMF can neither break chemical bonds nor cause ionization in living cells. The existing safety guideline of RF-EMF exposure recommended by the International Commission of Non-Ionizing Radiation Protection was based on the conclusion that high frequency exposure below the thermal threshold is unlikely to be associated with adverse health effects (ICNIRP, High frequency 100 kHz - 300 GHz). Nonetheless, various potential health effects of RF-EMF, including electromagnetic hypersensitivity, behavioral problems, degenerative diseases, fertility and reproductive issues, and biological effects such as changes to gene and protein expression, immune function, melatonin, cancers, and blood-brain barrier changes have been reported (BioInitiative Working Group, 2012). However, to date, researchers have not been able to establish a causal relationship between RF-EMF exposure below regulatory limits and potential health effects. In 2001, the International Agency for Research on Cancer classified RF-EMF as being possibly carcinogenic to humans (Group 2B).

RF-EMF exposure levels are highly variable, depending on the spatial and temporal location of the participants, and real RF-EMF exposure to people depends on their behavioral patterns as well as the surrounding environments. A previous study reported that total RF-EMF exposure increased between 20.1% and 57.1% within one year in an area of Switzerland and Belgium, and that the highest total RF-EMF levels occurred in public transportation areas (Urbinello et al., 2014b). Another study reported that RF-EMF levels have variability according to the type of area (business, downtown, or residence) and type of city, which result in 30% and 50% variability with respect to mobile phone base-station radiation, respectively (Urbinello et al., 2014a).

On the other hand, when an individual wears a personal exposure meter (PEM), the reading values at the device are affected by the human body. The body is composed of tissue which readily absorbs RF-EMF radiation and accordingly, the presence of the human body results in the decrease of the value measured by the PEM. For such a body shadowing effect, it was Bolte et al. (2016) suggested that correcting for the bias due to the attenuation increases accuracy of the personal exposure assessment (Bolte et al., 2016). However, in previous RF-EMF exposure studies, the bias compensation has been rarely considered.

There have been limited studies in Korea that report personal daily life RF-EMF exposure levels. Therefore, we aimed to assess the personal RF-EMF exposure levels of children and adults through their activities, with consideration of the body shadowing effect.

## 2. Material and methods

### 2.1. Study participants

We recruited 50 child-adult pairs (100 participants) within the Mothers and Children's Environmental Health (MOCEH) cohort (Kim et al., 2009) between September and

December 2016. We made a telephone call to invite individuals within the cohort to participate in this study, and recruited only those who agreed to install a smartphone application and measure their personal RF-EMF exposure. The children, aged between six and nine years, and their parents were living either in Seoul, a metropolitan area; Cheonan, a medium-sized urban area; or Ulsan, an industrial area, in South Korea. We measured RF-EMF exposure using a PEM and obtained time-activity diaries and questionnaire information from each participant. Nine participants were excluded due to mismatch between times recorded in the activity diary and in the PEM. Finally, 91 participants were included in the study. The study protocol was approved by the institutional review board of Dankook University and an informed written consent was obtained before enrollment.

### 2.2. Personal measurement of RF-EMF

RF-EMF measurements were performed using a PEM, ExpoM-RF®, developed by the Fields at Work company in Switzerland (http://www.fieldsatwork.ch/). The exposure meter was tailored to capture 15 Korean RF bands ranging from 87.5 MHz to 5875 MHz (Table S1). Participants carried the device for 48 hours and the measured values were recorded every 4 seconds. Values were left censored at half of the frequency-specific lower detection limit (0.003-0.05 V/m), and right censored at 5 V/m in the same manner as in a previous study (Sagar et al., 2016). Each left censored value, and the proportion of censored values among measured RF-EMFs in respect of activities and frequency bands, are shown in the supplementary materials (Table S2). These devices also recorded GPS coordinates.

### 2.3. Time-activity diary

At the same time as the RF-EMF measurement, participants were provided with a study phone, in which an activity diary application had been installed. The participants were requested to record 18 time-activities (at home [house/apartment, garden/balcony/terrace], at school [classroom, canteen/elsewhere], at work [own office, another office/meeting room, canteen/elsewhere], on the move [on foot/bicycle, bus, car, metro], outside, miscellaneous [cinema/theater/concert, friends/acquaintances/relatives, restaurant/café, shopping, sports center/fitness room, others]) into the activity diary. The study phone was set to flight-mode, and the other applications were technically locked.

### 2.4. Covariates

Personal characteristics and characteristics of cell phone and electronics usage (i.e. smartphone usage, call frequency and duration, text message application use, desktop and laptop PC usage) during measurement time were obtained using a questionnaire administered at the end of measurement period.

### 2.5. Compensation of body shadowing effect

Based on the hybrid model, the correction factor was used to compensate the body shadowing effect. The details on body shadowing effect and its correction factors was described elsewhere (Hwang et al., 2017). Briefly, the attenuation due to the body shadowing effect was measured with respect to the direct and diffused waves, respectively, and then the measured attenuation for each wave condition was combined to derive the hybrid model. The combination of the measured attenuation was possible using two factors: the K-factor and the factor representing the cross-polarization discrimination. By the attenuation combination, it can model the body shadowing effect occurring in a real RF-EMF exposure environment, in which the direct and diffused waves contribute to the body shadowing effect at the same time. During the attenuation measurement, a human phantom was used to simulate the body shadowing effect while enhancing the measurement reproducibility. For these reasons, the hybrid model makes it possible to estimate the attenuation by the body shadowing effect close to the attenuation occurring in a real RF-EMF exposure environment (Hwang et al., 2017).

The body shadowing compensation was conducted through multiplying the measured EMF strength of each relevant frequency band by the correction factor obtained from the hybrid model. The correction factors in a linear scale were 1.429, 1.429, 1.429, 1.603, 1.175, 1.175, and 1.567 for TV, 800DL, LTE900DL, LTE1800DL, WiBro, LTE2100DL and LTE2600DL, respectively, in which each symbol for the frequency bands is described in the supplementary materials (Table S1). The hybrid model was derived only at four frequency bands including 879, 1840, 2140, and 2650 MHz (Hwang et al., 2017); hence, the correction factor was obtained from the hybrid model whose frequency is closest to each of the measurement frequency bands. Because the body shadowing effect occurs at the downlink frequency bands, the correction factor was applied to the downlink only. Additionally, the correction factor was applied to the selected activities such as outside, moving on foot/bicycle, bus, car, metro, and shopping because the hybrid model is valid only for an outdoor environment (Hwang et al., 2017).

### 2.6. Statistical analysis

Data from PEM and activity diary were merged in respect of time, and the quality of the diary entries was evaluated. We checked for potential logical errors in the sequence of activities (e.g. home directly followed by school, without any commuting activity between) and checked the GPS of the relevant activity directly with Google Earth for correction, and corrected activities or activity times for obvious errors.

Descriptive statistics of RF-EMF by frequency bands and characteristics and the contribution proportion to total exposure were calculated. Body shadowing compensated power density was summarized as means for individuals and activity, and the natural logarithm transformed power density was modeled using a weighted linear mixed model with weights for the proportional number of observed times that included activities, regions, subjects, call frequency and duration, text message use, desktop and laptop PC use, and random intercept for repeated individuals. The significance level for tests was 0.05, and the R version 3.3.3 (Comprehensive R Archive Network: http://cran.r-project.org) was used.

## 3. Results

The general characteristics of the participants are shown in Table 1. Among 91 participants, fathers, mothers, and children comprised of 28.6%, 22.0% and 49.5%, respectively, with 27.5% of the residents living in Seoul, 40.7% in Ulsan, and 31.9% in Cheonan. The participants' call frequency for a day was as follows: 18.1% ≤1, 45.8% 2-5, and 36.1% ≥ 6 calls. The call duration for a day (minutes) was 53.0% for ≤1-5, 15.7% for 6-15, and 31.3% for ≥16. Regarding text number of messages for a day, 33.7% reported no use, 31.3% ≤10, and 34.9% >10. Forty percent of participants used a desktop PC, and 15% used a laptop.

Levels of radiofrequency radiation exposure with respect to activities and body shadowing compensation are shown in Table 2. In compensating for the body shadowing effect, the mean of total power density increased approximately 2.023, 1.976, 2.024, 1.939, 2.023 and 2.081 times for on foot/bicycle, bus, car, metro, outside and shopping, respectively. The body shadowing correction was not applied to other activities.

The geometric means (geometric standard deviations) of the total power density before body shadowing compensation were 36.6 (4.4) $\mu W/m^2$ for all participants, 44.6 (4.7) for fathers, 44.8 (4.8) for mothers, and 30.1 (4.0) for children (Table 3). Those for uplink were 0.2 (3.4), 0.2 (3.8), 0.2 (3.7), and 0.1 (2.9), and those for downlink were 17.1 (5.8), 19.3 (6.4), 21.7 (6.0), and 14.4 (5.3) for all, fathers, mothers, and children, respectively.

As illustrated in the Fig. 1, the contributions of each frequency band in all participants were 76.7%, 2.4%, 9.9%, 5.0%, 3.3%, and 2.6% for downlink, uplink, total WiFi, FM Radio, TV, and WiBro, respectively: those were 80.5%, 2.2%, 6.8%, 5.6%, 2.8%, and 2.0% in fathers, 77.7%, 2.5%, 11.0%, 3.0%, 2.7%, and 3.1% in mothers, and 71.6%, 2.7%, 12.2%, 6.2%, 4.5%, and 2.8% in children, respectively.

RF-EMF exposure levels with regard to subjects, regions, and body shadowing compensation is shown in Fig. 2. Seoul is a metropolitan area showing the highest level at 322 $\mu W/m^2$ compared to the Ulsan (124 $\mu W/m^2$) and Cheonan (121 $\mu W/m^2$). In compensating for the body shadowing effect, the total RF-EMF exposure increased approximately 1.4 times. The total RF-EMF levels for cell phone and electronics usage are shown in the supplementary materials (Fig. S1).

RF-EMF exposures by activities are shown in Fig. 3. Total RF-EMF was the highest at 4726 $\mu W/m^2$ in the metro. Downlink exposure was also the highest in the metro, followed by shopping; 4262 $\mu W/m^2$ and 1183 $\mu W/m^2$, respectively. Uplink exposure was the highest in cinema/theater/concert, followed by metro and bus; 50 $\mu W/m^2$, 48 $\mu W/m^2$ and 41 $\mu W/m^2$, respectively.

In a mutually adjusted mixed regression analysis, total RF-EMF, uplink, downlink, WiFi, and WiBro were also significantly highest in the metro, and total RF-EMF, downlink, and FM were significantly higher in Seoul than in Cheonan (Table 4).

## 4. Discussion

The total RF-EMF exposure level in Korean children and parents was 174.9 $\mu W/m^2$ on average, which is higher than those reported in previous studies (22.7 to 180 $\mu W/m^2$) (Bolte and Eikelboom, 2012; Frei et al., 2009; Roser et al., 2017; Thomas et al., 2008a; Thomas et al., 2008b; Thuróczy et al., 2008; Valic et al., 2009; Valic et al., 2015). However, median level (29.1 μW/m$^2$) of total RF-EMF in the present study was comparable with those in the previous studies (25.5 to 109.6 μW/m$^2$) (Bolte and Eikelboom, 2012; Frei et al., 2009; Roser et al., 2017; Thuróczy et al., 2008; Valic et al., 2009; Valic et al., 2015). In a study performed in Australian kindergarten children, the median level was 17.4 mW/m$^2$ (Total RF-EMF) and 9.9 mW/m$^2$ (downlink) (Bhatt et al., 2017), which were lower than those of children in the present study. The difference of RF-EMF personal exposure levels between studies might come from various differences such as study populations, type of area (urbanization), measurement devices, measured frequency bands, the summarizing method of measured values, and the methods of dealing with detection limits. Most of all, the fact that the present study included Seoul metropolitan city, a highly urbanized and densely wired area, while most previous studies on RF-EMF measurements were undertaken mainly in rural areas (Roser et al., 2017), would be a reason for the higher mean exposure level of the present study.

When the body shadowing effect was compensated in the present study, an increase by 1.4 times was estimated in the total RF-EMF exposure level. A previous study on personal exposure that considered a body shielding bias (Bhatt et al., 2016) reported a higher total exposure level than that reported in the present study: average (median) was 717.2 μW/m$^2$ (383.0 μW/m$^2$) versus 240.7 μW/m$^2$ (29.8 μW/m$^2$). The reason is likely due to the different way of correction between studies and a smaller correction factor in the present study (Table S3). The electromagnetic field incidents recorded on a PEM are composed of direct and diffused waves. The component of diffused wave, which is dominant in an urban or residential area due to more frequent wave reflections by buildings and walls, weakens the body shadowing effect (Hwang et al., 2017). The correction factor used by Bhatt et al.(2016) was derived from a measurement in a fully anechoic chamber reproducing only the direct wave while the factor in the present study was from the hybrid model, in which the correction factor is determined by the amount of the diffused wave (Hwang et al., 2017).

In Korea, Code Division Multiple Access 2000 and Wideband Code Division Multiple Access (a family of 2.5G or 3G mobile technology standards) subscribers have been decreased rapidly from 16 and 35 (2011) to 3.5 and 11 million (2016), respectively, whereas LTE subscribers increased from 0.12 (2012) to 46 million (2016) (Ministry of Science, ICT and Future Planning, Statistics for wireless communication services of Korea). Although the total number of mobile phone subscribers did not show a big increase (52 to 61 million) for the same periods, a significant transition between information technologies should be considered in the cumulative exposure assessment to improve its accuracy.

The finding of the lowest total RF-EMF levels at home and at school was consistent with findings in previous studies (Roser et al., 2017). In previous studies, the highest level of total RF-EMF was identified in transportation (Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010; Roser et al., 2017; Viel et al., 2009). Consistently, the highest total RF-EMF was also observed in the metro in the present study. The downlink exposure level was highest in the metro and followed by shopping. The uplink exposure level was higher in order: the cinema or concert hall area, metro, and bus transportation. The highest mean exposure relates to the activities with high people-density (Bolte and Eikelboom, 2012). Public transportation is the space to be commonly crowded and a higher uplink exposure can be expected. Furthermore, the metro usually passes through central part of the cities, where base-stations may be located densely.

The contributions of uplink and downlink to total RF-EMF exposure varied in several studies (37.5% and 12.7% in Bolte and Eikelboom, 2012; 29.1% and 32.0% in Frei et al., 2009; 67.2% and 19.8% in Roser et al., 2017). In the present study, the downlink exposure accounted for 76.7% total exposure and showed the highest contribution in Seoul. The various contribution proportions of each frequency to total exposure between studies may be related to where measurements have been performed. The downlink exposure contribution is related to the density of base-stations. High urbanization lead to an increasing RF-EMF exposure (Bolte, 2016), and the downlink exposure increases with the percentage of urban ground use (Bolte and Eikelboom, 2012). A possible explanation for the slight uplink exposure increase in children in the present study may be a result of longer mobile internet use, compared to adults.

This study has some limitations. First, with regard to representativeness, the participants were recruited as was convenient. Although it included three different regions of Korea, it is limited to generalize to whole Korea and other countries. Second, because half of the lower detection limit of the ISM5800 (WiFi 5) is relatively higher than the other frequency bands (Table S2), WiFi levels in our results might have been overestimated due to censored values. However, WiFi 5 contributed approximately 1.7% to the total RF-EMF exposure in the present study (not shown in results) and it would not have had a significant impact on our results. Third, we empirically selected specific activities to compensate for the body shadowing effect but an experimental verification was not performed for the chosen activities.

## 5. Conclusions

In conclusion, we found that base-station exposure was the largest contributor to personal measurements of RF-EMF in both parents and children in South Korea. Total and base-station RF-EMF exposure levels in Korea were higher than those reported in European countries and Australia.

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**CONFLICT OF INTEREST**

The authors have no conflicts of interest associated with the material presented in this paper

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Table 1. General characteristics of study participants.

| Questionnaire | | Study participants (N= 91) | | |
|---|---|---|---|---|
| Characteristics | Levels | n | % | Mean ± SD |
| **Subjects** | **Fathers** | 26 | 28.6 | |
| | Age | | | 40.4 ± 3.5 |
| | **Mothers** | 20 | 22 | |
| | Age | | | 40.5 ± 4.6 |
| | **Children** | 45 | 49.5 | |
| | Age | | | 8.5 ± 0.9 |
| | Gender, male | 23 | 51.1 | |
| **Regions** | Cheonan | 29 | 31.9 | |
| | Seoul | 25 | 27.5 | |
| | Ulsan | 37 | 40.7 | |
| **Call frequency** | ≤1 calls/day | 15 | 18.1 | |
| | 2-5 calls/day | 38 | 45.8 | |
| | ≥6 calls/day | 30 | 36.1 | |
| **Call duration** | ≤1-5 min/day | 44 | 53 | |
| | 6-15 min/day | 13 | 15.7 | |
| | ≥16 min/day | 26 | 31.3 | |
| **Text message** | No use | 28 | 33.7 | |
| | ≤10 msg/day | 26 | 31.3 | |
| | >10 msg/day | 29 | 34.9 | |
| **Desktop pc use** | No use | 52 | 59.8 | |
| | Use | 35 | 40.2 | |
| **Laptops pc use** | No use | 74 | 85.1 | |
| | Use | 13 | 14.9 | |

Table 2. Levels of radiofrequency radiation exposure by activities and body shadowing compensation (μW/m²).

| Activities | N (%) | Original measurement | | | | | | | Body shadowing compensation | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total | Uplink | Downlink | TOTWi | FM | TV | WiBro | Total | Uplink | Downlink | TOTWi | FM | TV | WiBro |
| | | Mean (SD) | | | | | | | | | | | | | |
| **At home** | | | | | | | | | | | | | | | |
| House/ apartment | 3214324 (69.83) | 79.0 (699.5) | 1.5 (180.5) | 38.1 (320.3) | 19.4 (569.1) | 11.0 (47.5) | 5.0 (29.8) | 4.0 (39.7) | - | - | - | - | - | - | - |
| Garden/balcony terrace | 274 (0.01) | 168.1 (713.1) | 0.9 (4.4) | 142.4 (707.9) | 3.3 (2.7) | 16.5 (32.5) | 4.1 (11.9) | 0.8 (2.3) | - | - | - | - | - | - | - |
| **At school** | | | | | | | | | | | | | | | |
| Classroom | 341834 (7.43) | 90.9 (579.2) | 2.7 (220.2) | 83.7 (532.7) | 2.2 (12.4) | 0.6 (2.5) | 0.7 (12.1) | 1.0 (12.1) | - | - | - | - | - | - | - |
| Canteen/elsewhere | 62828 (1.36) | 67.0 (307.3) | 0.9 (23.2) | 61.5 (303.8) | 2.2 (9.9) | 0.6 (3.1) | 0.8 (6.4) | 0.9 (10.2) | - | - | - | - | - | - | - |
| **At work** | | | | | | | | | | | | | | | |
| Own office | 314903 (6.84) | 376.0 (879.6) | 4.7 (149.6) | 338.3 (852.1) | 13.1 (93.0) | 4.3 (36.5) | 11.5 (139.4) | 4.1 (17.4) | - | - | - | - | - | - | - |
| Another office/meeting room | 39509 (0.86) | 361.9 (1,268.7) | 16.3 (621.3) | 241.2 (876.5) | 30.0 (180.2) | 12.3 (39.9) | 12.6 (79.8) | 49.5 (551.8) | - | - | - | - | - | - | - |
| Canteen/elsewhere | 13442 (0.29) | 266.4 (829.4) | 8.5 (149.6) | 247.7 (805.0) | 3.7 (10.7) | 1.1 (8.0) | 1.0 (6.6) | 4.4 (35.6) | - | - | - | - | - | - | - |
| **On the move** | | | | | | | | | | | | | | | |
| On foot/bicycle | 111569 (2.42) | 988.8 (4,167.8) | 25.1 (785.5) | 915.3 (4,010.6) | 29.8 (566.5) | 4.0 (43.5) | 7.5 (82.2) | 7.2 (95.8) | 2,000.8 (8,578.1) | 25.1 (785.5) | 1,916.7 (8,468.6) | 29.8 (566.5) | 4.0 (43.5) | 15.4 (167.8) | 9.9 (132.3) |
| Bus | 12577 (0.27) | 733.9 (2,199.2) | 40.5 (951.6) | 627.7 (1,796.6) | 26.3 (842.1) | 17.0 (60.4) | 15.8 (73.3) | 6.7 (39.3) | 1,450.3 (4,045.4) | 40.5 (951.6) | 1,325.1 (3,837.8) | 26.3 (842.1) | 17.0 (60.4) | 32.3 (149.6) | 9.2 (54.3) |
| Car | 162665 (3.53) | 583.5 (2,161.4) | 23.9 (770.6) | 530.0 (1,980.8) | 14.7 (323.1) | 2.7 (16.9) | 6.3 (109.6) | 6.0 (46.2) | 1,181.1 (4,230.4) | 23.9 (770.6) | 1,118.7 (4,125.4) | 14.7 (323.1) | 2.7 (16.9) | 12.8 (223.8) | 8.2 (63.8) |
| Metro | 9103 (0.20) | 4,725.9 (11,965.1) | 47.8 (614.7) | 4,261.5 (11,834.5) | 228.9 (974.4) | 8.1 (115.0) | 0.9 (5.7) | 178.8 (1,000.9) | 9,161.5 (23,918.1) | 47.8 (614.7) | 8,628.1 (23,836.6) | 228.9 (974.4) | 8.1 (115.0) | 1.8 (11.7) | 246.8 (1,381.9) |
| **Outside** | 59831 (1.30) | 496.5 (1,819.4) | 23.7 (985.4) | 430.0 (1,360.1) | 8.0 (290.1) | 6.9 (56.9) | 23.8 (428.4) | 4.1 (35.3) | 1,004.4 (3,208.8) | 23.7 (985.4) | 911.6 (2,868.1) | 8.0 (290.1) | 6.9 (56.9) | 48.5 (874.8) | 5.7 (48.7) |
| **Miscellaneous** | | | | | | | | | | | | | | | |
| Cinema/theater/concert | 4728 (0.10) | 110.1 (1,210.8) | 50.1 (1,191.2) | 54.2 (205.8) | 4.0 (19.4) | 0.3 (0.6) | 1.2 (26.3) | 0.4 (2.9) | - | - | - | - | - | - | - |
| Friends/acquaintances/relatives | 15290 (0.33) | 352.6 (829.6) | 2.0 (59.4) | 317.4 (810.2) | 9.0 (43.6) | 11.1 (18.5) | 4.3 (7.3) | 8.7 (43.8) | - | - | - | - | - | - | - |
| Restaurant/café | 44607 (0.97) | 262.1 (1,167.9) | 12.4 (539.4) | 231.7 (1,000.0) | 11.9 (194.7) | 1.4 (8.9) | 2.0 (42.1) | 2.7 (14.0) | - | - | - | - | - | - | - |
| Shopping | 9746 (0.21) | 1,229.4 (3,648.5) | 3.4 (37.2) | 1,182.9 (3,637.9) | 25.9 (145.1) | 2.6 (13.7) | 2.4 (59.3) | 12.2 (138.3) | 2,557.9 (7,812.2) | 3.4 (37.2) | 2,504.2 (7,803.4) | 25.9 (145.1) | 2.6 (13.7) | 4.9 (121.1) | 16.8 (190.9) |
| Sports center/fitness room | 18083 (0.39) | 569.6 (1,764.6) | 0.9 (23.0) | 562.9 (1,761.4) | 3.0 (5.5) | 0.8 (2.5) | 0.2 (0.8) | 1.8 (9.0) | - | - | - | - | - | - | - |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Others | 167803 (3.65) | 313.8 (1,449.9) | 9.4 (441.5) | 269.1 (1,336.7) | 9.4 (283.7) | 7.6 (42.7) | 15.1 (137.3) | 3.1 (28.8) | - | - | - | - | - | - | - |

- : It is the same as the original measured value. Body shadowing compensation was not applied.
Total : sum of all measured 15 frequency bands (Table S1) as power density unit, Uplink : 800UL + LTE900UL + LTE1800UL + LTE2100UL + LTE2600UP, Downlink : 800DL + LTE900DL + LTE1800DL + LTE2100DL + LTE2600DL, WiFi : ISM 5800(WiFi 5) + ISM 2400(WiFi 2). Each symbol for the frequency bands is described in Table S1.
Body shadowing compensation was applied that measured E-field was multiplied by body shadowing factor (correction factor) for TV, 800DL, LTE900DL, LTE1800DL, WiBro, LTE2100DL, LTE2600DL (1.429, 1.429, 1.429, 1.603, 1.175, 1.175, 1.567, respectively) for activities of outside, moving on foot/by bicycle, bus, car, metro and shopping.

Table 3. Distribution of radiofrequency radiation exposure by characteristics (μW/m$^2$).

| | | Original measurement | | | | | | | Body shadowing compensation | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Characteristics** | **Bands** | Mean (SD) | gMean (gSD) | Min. | 25 percentile | 50 percentile | 75 percentile | Max. | Mean (SD) | gMean (gSD) | Median (IQR) |
| All | Total | 174.9 (1,255.1) | 36.6 (4.4) | 2.10 | 11.92 | 29.08 | 90.55 | 268909.89 | 240.7 (2,169.4) | 38.5 (4.7) | 29.8 (83.8) |
| | Uplink | 4.3 (307.4) | 0.2 (3.4) | 0.06 | 0.07 | 0.09 | 0.21 | 68727.16 | 4.3 (307.4) | 0.2 (3.4) | 0.1 (0.1) |
| | Downlink | 134.1 (1,085.0) | 17.1 (5.8) | 0.06 | 5.04 | 13.72 | 48.62 | 260122.37 | 198.8 (2,065.3) | 18.1 (6.2) | 14.1 (46.7) |
| | WiFi | 17.3 (496.9) | 3.5 (2.7) | 1.68 | 1.82 | 2.52 | 4.52 | 91449.06 | 17.3 (496.9) | 3.5 (2.7) | 2.5 (2.7) |
| | FM | 8.8 (43.5) | 0.8 (5.7) | 0.27 | 0.27 | 0.28 | 1.63 | 10586.70 | 8.8 (43.5) | 0.8 (5.7) | 0.3 (1.4) |
| | TV | 5.8 (75.7) | 0.1 (10.1) | 0.02 | 0.02 | 0.06 | 0.40 | 66365.81 | 6.6 (123.5) | 0.1 (10.3) | 0.1 (0.4) |
| | WiBro | 4.6 (78.8) | 0.4 (7.0) | 0.02 | 0.10 | 0.38 | 1.57 | 28756.72 | 4.9 (91.6) | 0.4 (7.0) | 0.4 (1.5) |
| Fathers | Total | 226.9 (1,326.0) | 44.6 (4.7) | 2.12 | 13.83 | 32.44 | 114.51 | 205046.66 | 318.4 (2,384.8) | 48.0 (5.0) | 33.9 (110.0) |
| | Uplink | 4.9 (305.3) | 0.2 (3.8) | 0.06 | 0.07 | 0.10 | 0.27 | 66386.66 | 4.9 (305.3) | 0.2 (3.8) | 0.1 (0.2) |
| | Downlink | 182.7 (1,237.5) | 19.3 (6.4) | 0.06 | 5.08 | 13.96 | 58.93 | 203971.74 | 271.9 (2,314.0) | 21.0 (7.0) | 14.4 (60.3) |
| | WiFi | 15.5 (249.7) | 4.4 (2.9) | 1.68 | 2.10 | 3.06 | 5.93 | 66368.20 | 15.5 (249.7) | 4.4 (2.9) | 3.1 (3.8) |
| | FM | 12.7 (70.3) | 0.8 (5.7) | 0.27 | 0.27 | 0.28 | 1.50 | 10586.70 | 12.7 (70.3) | 0.8 (5.7) | 0.3 (1.2) |
| | TV | 6.4 (124.9) | 0.1 (9.6) | 0.02 | 0.02 | 0.07 | 0.38 | 66365.81 | 8.3 (220.7) | 0.2 (9.9) | 0.1 (0.4) |
| | WiBro | 4.6 (63.8) | 0.5 (6.7) | 0.02 | 0.15 | 0.43 | 1.52 | 22853.58 | 5.1 (80.9) | 0.5 (6.7) | 0.4 (1.4) |
| Mothers | Total | 245.4 (1,604.8) | 44.8 (4.8) | 2.10 | 13.82 | 31.28 | 134.35 | 268909.89 | 353.4 (2,993.9) | 47.3 (5.2) | 31.8 (129.3) |
| | Uplink | 6.2 (363.7) | 0.2 (3.7) | 0.06 | 0.07 | 0.11 | 0.34 | 68727.16 | 6.2 (363.7) | 0.2 (3.7) | 0.1 (0.3) |
| | Downlink | 190.7 (1,447.9) | 21.7 (6.0) | 0.06 | 6.33 | 15.49 | 61.74 | 260122.37 | 297.3 (2,904.3) | 23.2 (6.5) | 15.9 (61.1) |
| | WiFi | 27.1 (544.0) | 4.2 (2.9) | 1.68 | 2.00 | 3.11 | 5.82 | 66394.96 | 27.1 (544.0) | 4.2 (2.9) | 3.1 (3.8) |
| | FM | 7.4 (19.2) | 0.9 (6.4) | 0.27 | 0.27 | 0.28 | 2.96 | 1450.14 | 7.4 (19.2) | 0.9 (6.4) | 0.3 (2.7) |
| | TV | 6.6 (46.9) | 0.2 (9.2) | 0.02 | 0.02 | 0.12 | 0.56 | 5216.47 | 7.3 (59.5) | 0.2 (9.4) | 0.1 (0.6) |
| | WiBro | 7.5 (97.1) | 0.7 (7.1) | 0.02 | 0.20 | 0.64 | 2.25 | 28756.72 | 8.1 (126.6) | 0.7 (7.1) | 0.6 (2.1) |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Children | Total | 116.2 (1,018.7) | 30.1 (4.0) | 2.10 | 10.29 | 26.17 | 72.17 | 238200.88 | 149.8 (1,523.7) | 31.2 (4.2) | 26.8 (63.9) |
| | Uplink | 3.1 (281.0) | 0.1 (2.9) | 0.06 | 0.07 | 0.08 | 0.16 | 66440.67 | 3.1 (281.0) | 0.1 (2.9) | 0.1 (0.1) |
| | Downlink | 83.2 (763.5) | 14.4 (5.3) | 0.06 | 4.58 | 12.71 | 41.70 | 196892.59 | 116.5 (1,364.7) | 15.0 (5.6) | 13.0 (38.7) |
| | WiFi | 14.2 (571.3) | 2.9 (2.3) | 1.68 | 1.75 | 2.00 | 3.44 | 91449.06 | 14.2 (571.3) | 2.9 (2.3) | 2.0 (1.7) |
| | FM | 7.3 (29.6) | 0.8 (5.4) | 0.27 | 0.27 | 0.29 | 1.65 | 1571.48 | 7.3 (29.6) | 0.8 (5.4) | 0.3 (1.4) |
| | TV | 5.2 (43.1) | 0.1 (10.6) | 0.02 | 0.02 | 0.04 | 0.37 | 50771.84 | 5.4 (44.8) | 0.1 (10.8) | 0.0 (0.4) |
| | WiBro | 3.3 (77.3) | 0.3 (6.8) | 0.02 | 0.07 | 0.27 | 1.38 | 13974.70 | 3.4 (78.1) | 0.3 (6.8) | 0.3 (1.3) |
| Activity: | Total | 120.5 (917.9) | 26.6 (4.1) | 2.10 | 9.06 | 21.67 | 56.21 | 163920.01 | 79.0 (699.5) | 28.3 (3.5) | 23.4 (54.1) |
| At home | Uplink | 4.4 (310.7) | 0.1 (3.0) | 0.06 | 0.07 | 0.09 | 0.18 | 68727.16 | 1.5 (180.5) | 0.1 (2.5) | 0.1 (0.1) |
| | Downlink | 87.5 (430.9) | 13.3 (5.9) | 0.06 | 3.89 | 12.15 | 38.40 | 99476.03 | 38.1 (320.4) | 11.5 (4.2) | 10.1 (24.3) |
| | WiFi | 21.0 (722.1) | 3.8 (2.6) | 1.68 | 1.90 | 2.75 | 5.27 | 91449.06 | 19.4 (569.1) | 3.8 (2.7) | 2.8 (3.2) |
| | FM | 0.5 (2.1) | 0.3 (1.7) | 0.27 | 0.27 | 0.27 | 0.27 | 928.15 | 11.0 (47.5) | 1.0 (6.4) | 0.3 (2.7) |
| | TV | 1.2 (21.4) | 0.1 (6.6) | 0.02 | 0.02 | 0.07 | 0.29 | 10584.58 | 5.0 (29.8) | 0.1 (9.6) | 0.1 (0.3) |
| | WiBro | 5.9 (98.8) | 0.4 (7.6) | 0.02 | 0.09 | 0.27 | 1.49 | 13974.71 | 4.0 (39.7) | 0.5 (5.7) | 0.4 (1.5) |
| Region: | Total | 79.0 (699.5) | 28.3 (3.5) | 2.10 | 11.02 | 23.45 | 65.17 | 238200.88 | 153.6 (1,118.5) | 28.0 (4.4) | 22.0 (49.5) |
| Cheonan | Uplink | 1.5 (180.5) | 0.1 (2.5) | 0.06 | 0.07 | 0.08 | 0.14 | 68727.16 | 4.4 (310.7) | 0.1 (3.0) | 0.1 (0.1) |
| | Downlink | 38.1 (320.4) | 11.5 (4.2) | 0.06 | 4.36 | 10.10 | 28.63 | 171100.47 | 120.1 (757.7) | 14.2 (6.3) | 12.5 (36.4) |
| | WiFi | 19.4 (569.1) | 3.8 (2.7) | 1.68 | 1.89 | 2.78 | 5.04 | 91449.06 | 21.0 (722.1) | 3.8 (2.6) | 2.8 (3.4) |
| | FM | 11.0 (47.5) | 1.0 (6.4) | 0.27 | 0.27 | 0.32 | 2.93 | 1939.24 | 0.5 (2.1) | 0.3 (1.7) | 0.3 (0.0) |
| | TV | 5.0 (29.8) | 0.1 (9.6) | 0.02 | 0.02 | 0.06 | 0.35 | 1790.20 | 1.6 (36.6) | 0.1 (6.8) | 0.1 (0.3) |
| | WiBro | 4.0 (39.7) | 0.5 (5.7) | 0.02 | 0.14 | 0.42 | 1.63 | 16864.67 | 6.0 (99.6) | 0.4 (7.6) | 0.3 (1.4) |

gMean : geometric mean, gSD : geometric standard deviation, Min. : minimum, Max.: maximum
Total : sum of all measured 15 frequency bands (Table S1) as power density unit, Uplink : 800UL + LTE900UL + LTE1800UL + LTE2100UL + LTE2600UP, Downlink : 800DL + LTE900DL + LTE1800DL + LTE2100DL + LTE2600DL, WiFi : ISM 5800(WiFi 5) + ISM 2400(WiFi 2). Each symbol for the frequency bands is described in Table S1.
Body shadowing compensation was applied that measured E-field was multiplied by body shadowing factor (correction factor) for TV, 800DL, LTE900DL, LTE1800DL, WiBro, LTE2100DL, LTE2600DL (1.429, 1.429, 1.429, 1.603, 1.175, 1.175, 1.567, respectively) for activities of outside, moving on foot/by bicycle, bus, car, metro and shopping.

Table 4. Body shadowing compensated radiofrequency radiation exposure levels using weighted linear mixed model.

| Characteristics | Total | Downlink | Uplink | WiFi | FM | TV | WiBro |
|---|---|---|---|---|---|---|---|
| | Fold-change (p-value) | | | | | | |
| **Activities** | | | | | | | |
| Home (ref) | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| School | 1.38 (0.02) | 3.17 (<0.01) | 0.95 (0.81) | 0.31 (<0.01) | 0.37 (<0.01) | 0.75 (0.28) | 0.62 (0.02) |
| Work | 3.47 (<0.01) | 6.16 (<0.01) | 3.65 (<0.01) | 0.90 (0.40) | 0.58 (<0.01) | 1.91 (0.02) | 1.90 (<0.01) |
| Miscellaneous | 4.31 (<0.01) | 8.20 (<0.01) | 4.09 (<0.01) | 1.01 (0.93) | 0.83 (0.35) | 3.71 (<0.01) | 1.57 (0.06) |
| Outside | 14.79 (<0.01) | 29.59 (<0.01) | 9.62 (<0.01) | 0.62 (0.08) | 1.15 (0.72) | 16.88 (<0.01) | 2.92 (0.02) |
| Bus/car | 18.86 (<0.01) | 46.58 (<0.01) | 16.83 (<0.01) | 1.00 (0.98) | 1.42 (0.13) | 23.82 (<0.01) | 5.24 (<0.01) |
| On foot/bycicle | 26.48 (<0.01) | 66.47 (<0.01) | 8.19 (<0.01) | 1.19 (0.37) | 1.00 (1.00) | 6.97 (<0.01) | 6.52 (<0.01) |
| Metro | 88.93 (<0.01) | 198.77 (<0.01) | 40.41 (<0.01) | 17.12 (<0.01) | 0.90 (0.91) | 1.40 (0.82) | 78.64 (<0.01) |
| **Regions** | | | | | | | |
| Cheonan (ref) | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Seoul | 2.26 (<0.01) | 3.09 (<0.01) | 0.63 (0.26) | 0.65 (0.19) | 7.34 (<0.01) | 2.07 (0.26) | 2.10 (0.10) |
| Ulsan | 1.23 (0.40) | 1.34 (0.32) | 0.74 (0.39) | 0.66 (0.14) | 2.01 (0.07) | 0.62 (0.37) | 1.32 (0.47) |
| **Subjects** | | | | | | | |
| Children (ref) | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Mothers | 1.09 (0.81) | 1.49 (0.37) | 1.06 (0.92) | 1.32 (0.51) | 0.52 (0.26) | 0.98 (0.98) | 0.89 (0.84) |
| Fathers | 1.14 (0.70) | 1.53 (0.33) | 0.74 (0.54) | 1.17 (0.69) | 0.64 (0.42) | 0.82 (0.80) | 0.81 (0.71) |

Total : Sum of all measured 15 frequency bands (Table S1) as power density unit, Uplink : 800UL + LTE900UL + LTE1800UL + LTE2100UL + LTE2600UP, Downlink : 800DL + LTE900DL + LTE1800DL + LTE2100DL + LTE2600DL, WiFi : ISM 5800(WiFi 5) + ISM 2400(WiFi 2). Each symbol for the frequency bands is described in Table S1.
Body shadowing compensation was applied that measured E-field was multiplied by body shadowing factor (correction factor) for TV, 800DL, LTE900DL, LTE1800DL, WiBro, LTE2100DL, LTE2600DL (1.429, 1.429, 1.429, 1.603, 1.175, 1.175, 1.567, respectively) for activities of outside, moving on foot/by bicycle, bus, car, metro and shopping.
Body shadowing compensated power density was summarized as mean by individuals*activity (n=439). Natural logarithm transformed power density was modeled by using weighted linear mixed model with weights for proportional number of observed times adjusted for call frequency and duration, text message use, desktop and laptops pc use and random intercept for repeated individuals.

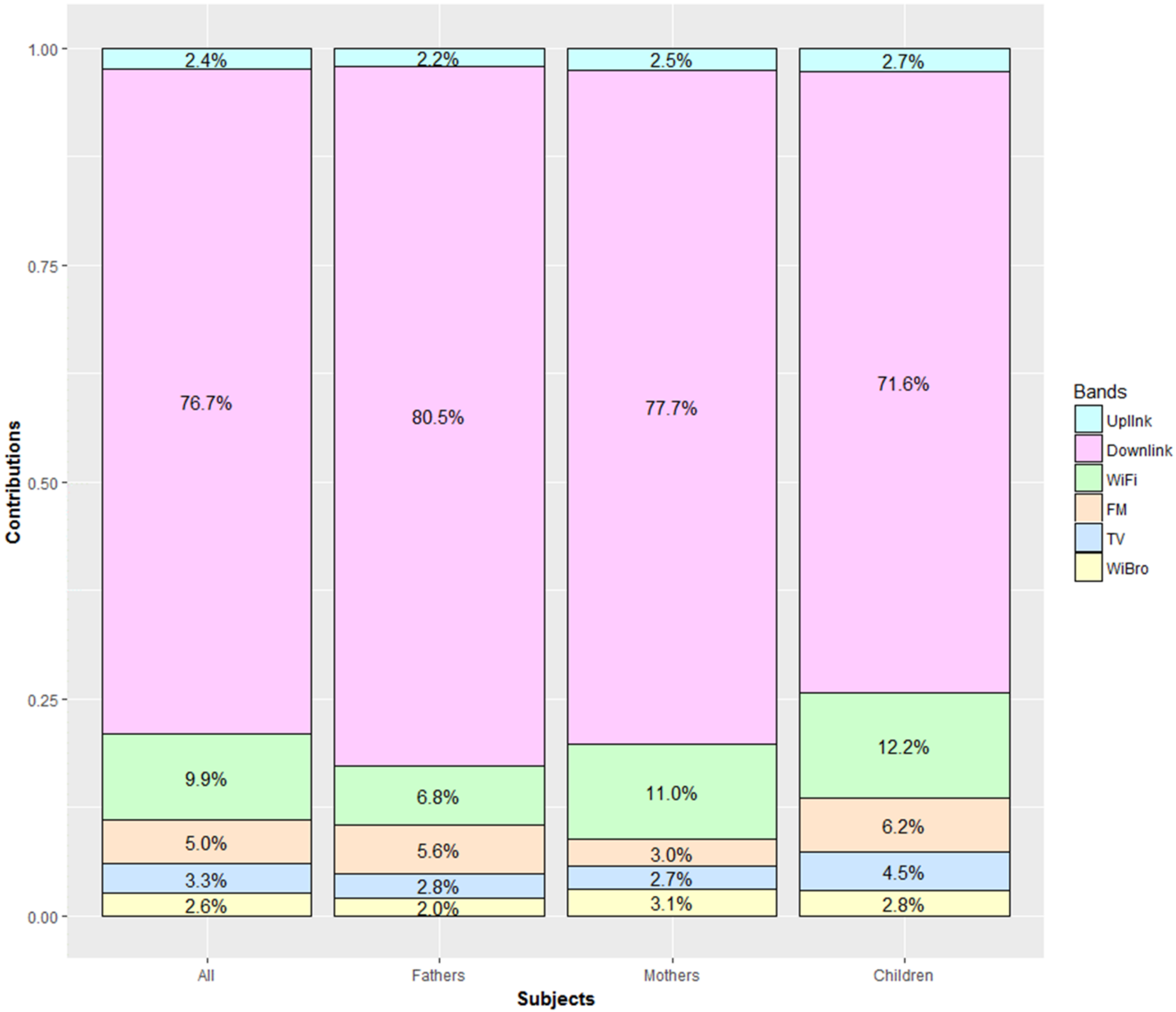


Figure 1. Contribution of each frequency bands to the total RF-EMF exposure in Korean children and parents.

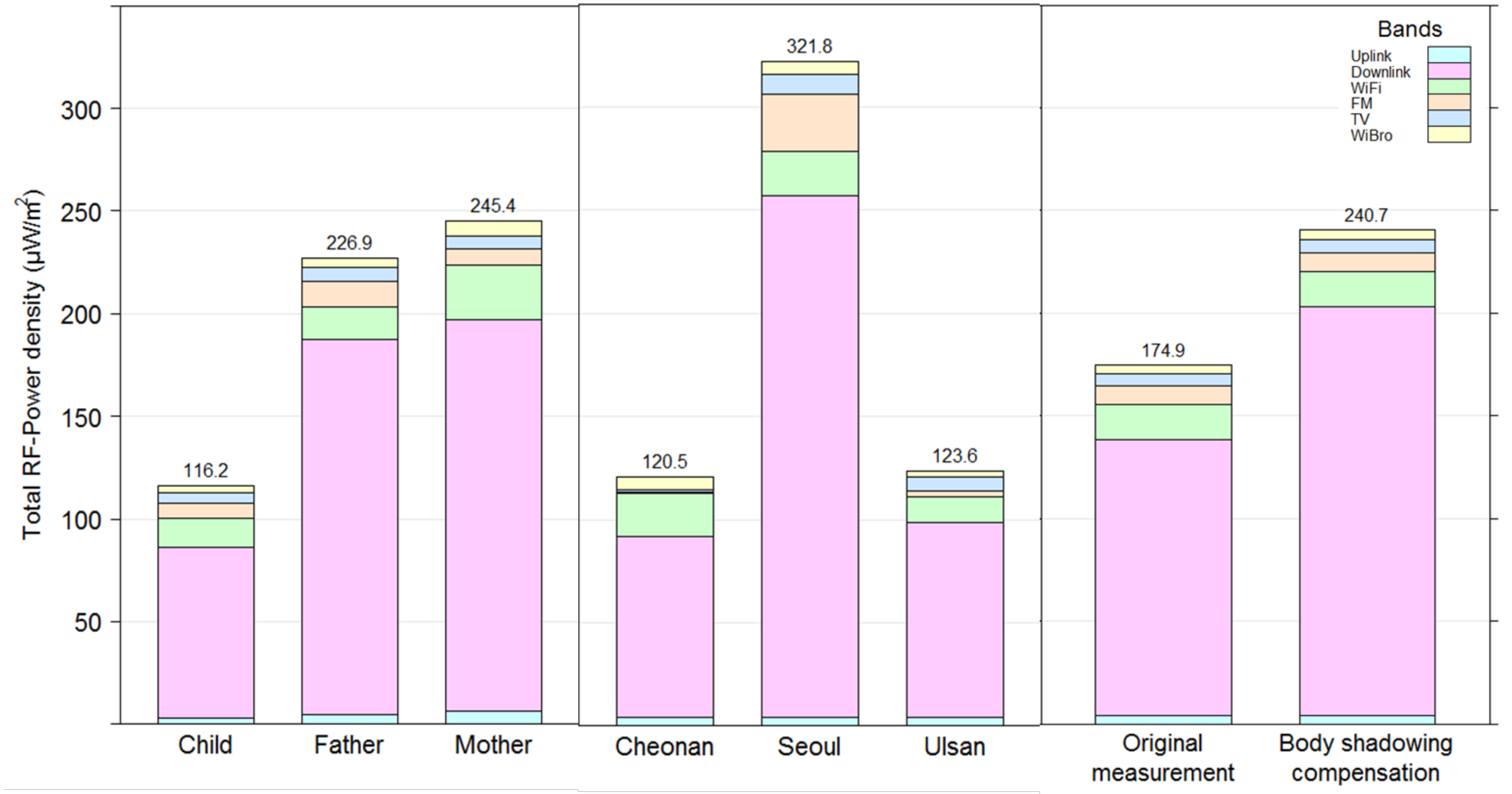


Figure 2. RF-EMF exposure levels by subjects, regions and body shadowing compensation in Korean children and parents.

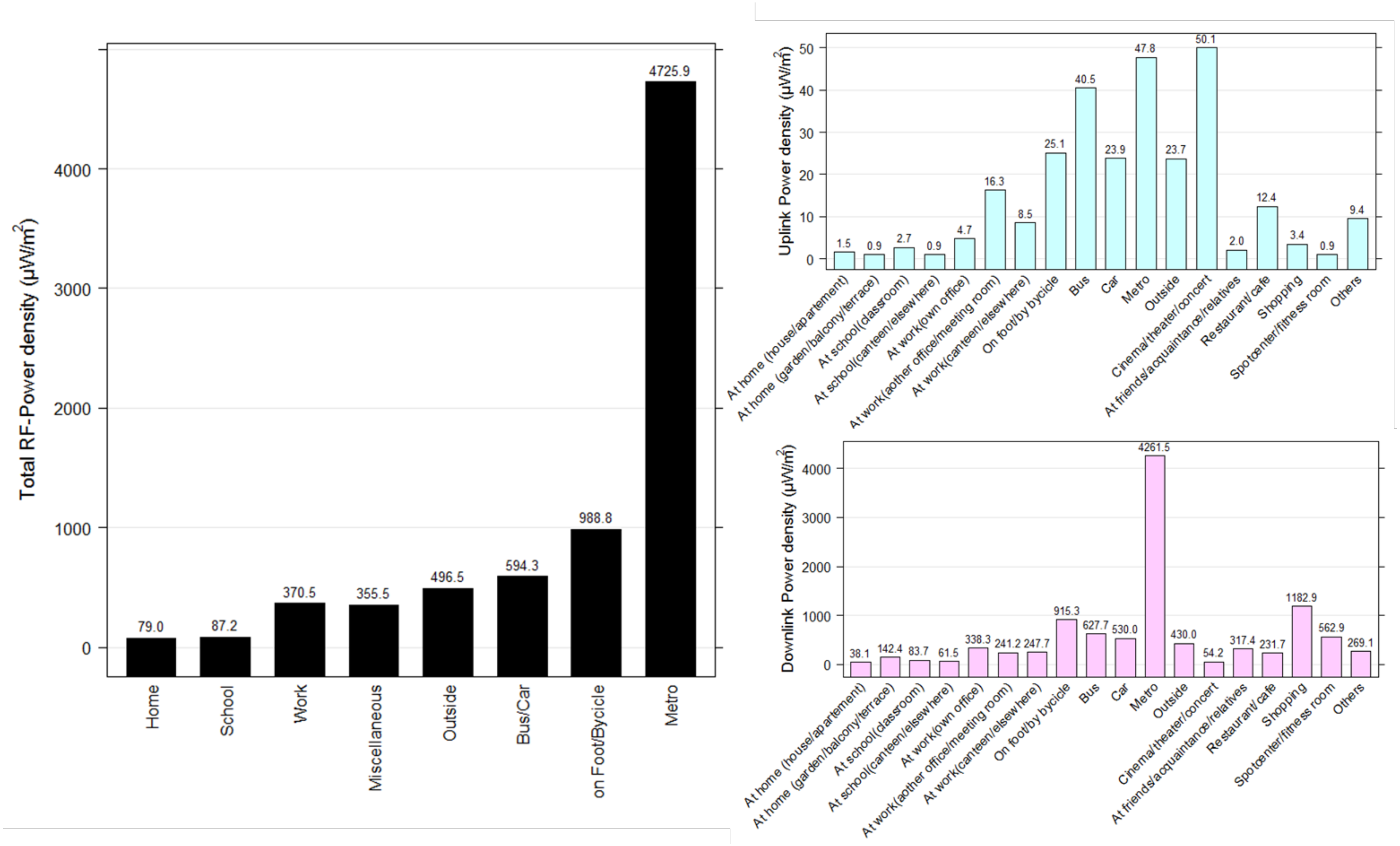


Figure 3. RF-EMF exposure levels by activities in Korean children and parents.