Assessment of Exposure to Radio Frequency Electromagnetic Fields From Smart Utility Meters in GB; Part II) Numerical Assessment of Induced SAR Within the Human Body

Muhammad R. A. Qureshi,1* Yasir Alfadhl,1 Xiaodong Chen,1 Azadeh Peyman,2 Myron Maslanyj,2 and Simon Mann2

1School of Electronic Engineering and Computer Science, Queen Mary University of London, London, United Kingdom
2Radiation Dosimetry Department, Public Health England, Oxford, United Kingdom

Human body exposure to radiofrequency electromagnetic waves emitted from smart meters was assessed using various exposure configurations. Specific energy absorption rate distributions were determined using three anatomically realistic human models. Each model was assigned with age- and frequency-dependent dielectric properties representing a collection of age groups. Generalized exposure conditions involving standing and sleeping postures were assessed for a home area network operating at 868 and 2,450 MHz. The smart meter antenna was fed with 1 W power input which is an overestimation of what real devices typically emit (15 mW max limit). The highest observed whole body specific energy absorption rate value was 1.87 mW kg\(^{-1}\) within the child model at a distance of 15 cm from a 2,450 MHz device. The higher values were attributed to differences in dimension and dielectric properties within the model. Specific absorption rate (SAR) values were also estimated based on power density levels derived from electric field strength measurements made at various distances from smart meter devices. All the calculated SAR values were found to be very small in comparison to International Commission on Non-Ionizing Radiation Protection limits for public exposure. Bioelectromagnetics. 39:200–216, 2018. © 2017 The Authors. Bioelectromagnetics Published by Wiley Periodicals LLC on behalf of Bioelectromagnetics Society

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INTRODUCTION

With the rapid move toward smart energy ecosystems, including key components such as smart grids, smart homes (including smart appliances, gateways), and utilities, smart meters (SMs) have relied on wireless technologies to maintain data communications. The concept of smart grids has evolved to provide efficient production and distribution of energy resources. SMs act as interface points between the smart grid and home appliances. This technology allows remote readings of water or energy meters (electricity, gas), and is expected to be used in the majority of UK households by the year 2020 [2010 to 2015 Government policy: Household energy, 2015; Department of Energy and Climate Change, 2013; Smart Metering, 2014; Scottish Power, 2015; Ofgem, 2016].

Home area networks (HANs) are typically used to monitor utility meters through a number of wirelessly connected devices in the household. Wide area networks (WANs) can also be used to wirelessly transmit and receive data between meters and central database stations, thus streamlining the billing process and enabling troubleshooting of systems and analysis of collected energy usage data. The fundamental working architecture of SMs is illustrated schematically in Figure 1. The SMs under consideration operate the HAN mainly using a ZigBee band [EET Asia, 2013] within the Industrial Scientific and Medical (ISM) 2,450 MHz spectrum region. ZigBee is

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*Correspondence to: M. R. A. Qureshi, School of Electronic Engineering and Computer Science, Queen Mary University of London, Mile End Road, London E1 4NS, UK.
E-mail: m.r.a.qureshi@qmul.ac.uk

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based on the IEEE-802.15.4 standard [Demystifying 802.15.4 and ZigBee, 2008], which specifies two communication bands relevant to this study: 868 MHz in Europe and 2,450 MHz worldwide.

The distances between the various HAN system components are expected to be relatively short. This assumption is in line with the views of the government department leading the smart meter program, which suggest that in-home display (IHD) devices are more likely to be placed near communication hubs (Comm-Hub) [Department of Energy and Climate Change, 2013]. In general, it is expected that the distance between the Comm-Hub and IHD devices will be much less than 100 meters (m) in the vast majority of houses.

Radiofrequency (RF) electromagnetic (EM) waves emitted from SM devices may interact with the human body such as to produce heating if the RF signals are very strong. There has been some concern among the public about the installation of SMs in the home, and the possibility of adverse health effects arising from exposure to radio signals from such devices. Although recent studies in Canada have confirmed that the emission levels are likely to be safe [Health Canada, 2011], this study was carried out to provide quantitative data to help put the exposures into context when addressing potential health concerns. International exposure guidelines, such as those published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in 1998 and the IEEE Std 1528-2013, specify whole body specific energy absorption rate (WBSAR), and localized SAR averaged within 10 g of tissue to limit exposure at radio frequencies. SAR is very difficult to measure directly inside the human body; therefore, numerical methods, such as the finite-difference time domain (FDTD) technique and anatomically realistic voxel models [Dimbylow, 1997, 2002, 2005; Dimbylow and Bolch, 2007], are utilized for calculating SAR levels that are likely to arise inside the body as a result of such exposures.

The purpose of this study was to evaluate the EM energy absorption likely to occur in the human body as a result of exposure to RF signals produced by smart meter HANs. Two generalized exposure scenarios were considered (as shown in Figure 2) using three numerical models, representing a sample of the population, namely: a 23-year-old female (NAOMI [Dimbylow, 2005]), a 34-year-old male (NORMAN [Dimbylow, 2005]), and a 7-year-old child (EARTHA [Bakker et al., 2010; ITIS, 2015]). Age- and frequency-dependent dielectric values were assigned as accurately as possible to represent the target tissues and render high accuracy in terms of the EM assessment. Numerical calculations were performed at model discretization resolutions of 2 and 1.4 mm for adults and child, respectively, at 868 and 2,450 MHz bands. The resulting induced averaged and maximum SAR distributions were compared with the SAR basic restrictions published by ICNIRP.

MATERIALS AND METHODS

Prior to initiating the SAR calculations phase, it was necessary to assess the accuracy and ability of the numerical tools in simulating the source signals. Various general purpose telemetry (GPT) and ISM band antennas were modeled based on parameters similar to the ones found in Comm-Hub and IHD devices [Peyman et al., 2017]. Numerical models of both antennas were designed and optimized to operate at the 868 and 2,450 MHz band, respectively. The radiation patterns resulting from both antennas (868 and 2,450 MHz bands) are shown in Figures 3 and 4. The angle ($\theta = 0, \phi = 0$) was toward the person in both frequency bands in all SM antenna exposure scenarios.

Numerical anatomical human models representing a sample of the population were configured and modeled using an established commercially available computation technique, namely Finite Integral Technique (FIT)-based CST Microwave Studio (MWS) [CST, 2014]. The FIT method is equivalent to the FDTD method, but has some advantages in representing irregular, curved, or thin structures. Both FDTD
and FIT methods are inherently identical in the way they resolve Maxwell’s equations in the differential and integral forms, respectively. The numerical models were simulated with very fine Cartesian volume cells (voxels) with resolutions of up to 2 mm, to ensure adequate representation of each organ and to satisfy numerical stability requirements.

The dielectric properties for both adult models (NAOMI and NORMAN) at two different frequencies, i.e., 868 and 2450 MHz, were calculated based on Cole-Cole formulations [Peyman and Gabriel, 2010]. The calculations were based on the IFAC online calculator, which is based on data reported from Gabriel [1996a,b,c] I, II, III. Data from Peyman and Gabriel [2010] were used for tissues missing in the 1996 database. Where no data were available for a particular tissue, adjustments and replacements were made to assign values from tissues with similar compositions. Furthermore, the age-dependent dielectric properties of the 7-year-old IITIS female child model were extrapolated from the available measured data of porcine tissues using a curve-fitting technique to map age-dependent properties to their appropriate human equivalent ones [Peyman and Gabriel, 2010, 2012].

Details of the validation studies and numerical stability conditions, as well as modeling and selection of dielectric properties for all age groups, are discussed in detail in the next section. The resulting exposures are then assessed in relation to the guidelines shown in Table 1.
Discretization of the Numerical Models (Voxel Models)

Adult Voxel models. Two adult voxel models (one female and one male) were used in the evaluation. The female model is based on Public Health England’s (PHE) voxelized 23-year-old female model (NAOMI), which is constructed from 791 slices along the body’s long axis, with 294 × 124 voxels in the horizontal plane. By considering voxel dimensions of 1.9, 2.0, and 2.0 mm in the x, y, and z voxel axis respectively, the resulting model has a height of 1.63 m and a mass of around 65 kg. These parameters are very close to those presented in Dimbylow [2005], which produced values of 1.63 m and 60 kg, with the difference in mass attributed to differences in voxel dimensions and mass densities used. Figure 5 shows a representation of the NAOMI model, with the opacity of the voxels varied to display the various body organs and tissue types. There were 40 different tissue types modeled in NAOMI. Each of the tissue-voxel types were populated with their corresponding dielectric parameters, calculated from IFAC database [IFAC, 2015].

The adult 34-year-old male model is based on PHE’s voxelized male model (NORMAN), which is constructed from 871 slices along the body’s long axis, with 148 × 277 voxels in the horizontal plane. The computed male adult model of NORMAN is 1.76 m tall and weighs around 76 kg with voxel dimensions of 1.9, 2.0, and 2.0 mm in each of the voxel axis. These dimensions are very close to those reported in Dimbylow [2005], where the adult male has a height of 1.76 m and mass of 73 kg. The difference in weight is attributed to differences in mass densities used, as mentioned in the previous section. The dielectric properties of the 38 different tissue types included in NORMAN were also calculated from the online database [IFAC, 2015].

Child Voxel model. The 7-year-old female child model is based on the ITIS EARTHA virtual human

| TABLE 1. ICNIRP Basic Restriction Levels for Occupational and General Public Exposure |
|---------------------------------|-----------------|-----------------|-----------------|
| Exposure characteristics       | Frequency of interest | WBSAR (W kg⁻¹) | Localized SAR for head and trunk (W kg⁻¹) | Localized SAR for limbs (W kg⁻¹) |
|--------------------------------|-----------------|-----------------|-----------------|-----------------|
| Occupational exposure          | 862–868 MHz     | 0.4             | 10               | 20               |
| General public exposure        | 2.4–2.4835 GHz  | 0.08            | 2                | 4                |
|                               | 862–868 MHz     |                 |                  |                  |
|                               | 2.4–2.4835 GHz  |                 |                  |                  |

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model, which is 0.965 m tall. The voxel dimensions are 1.4, 1.4, and 1.4 mm in x, y, and z axis. There are 300 × 122 voxels in each horizontal plane. A few refinements were made to the dielectric properties of the tissues to ensure that they are valid for the given age and for the operational frequencies considered in this study (868 and 2,450 MHz). This female child model has 75 different tissue types [ITIS, 2015]. The dielectric properties of tissues used in each of the models were determined from Cole–Cole models [Gabriel et al., 1996a, b, c; Peyman and Gabriel, 2010, 2012]. Dielectric properties for the child model were calculated using interpolation equations that are calculated from 10, 50, and 250 kg pig data [Peyman and Gabriel, 2010, 2012]. Moreover, growth curve data for a 21.3 kg pig [Pigs Growth, 2015] were used to interpolate the dielectric properties for the child model as shown in Figure 6, and the same method

![Volume rendered images of female model (NAOMI)](image)

Fig. 5. Volume rendered images of female model (NAOMI): (a) Outside surface; (b) Skin and skeleton; (c) Skeleton with a few internal organs (Skin, Fat, and Muscle removed); (d) 240 million cell mesh generated by adopting technique mentioned in setup and computational method section in order to satisfy stability condition. Rendering resolution is 2 mm × 2 mm × 2 mm.

![Dielectric properties of 7-year-old child](image)

Fig. 6. Dielectric properties of 7-year-old child, calculated by extrapolation of pig data and using curve fitting techniques; (a) Permittivity of Spinal Cord at 868 MHz; (b) Conductivity of Spinal Cord at 868 MHz.
was applied for all tissues to get equivalent data for a 7-year-old child. In recent years, pigs have been found to be similar to humans in terms of body organ development. According to Pigs Growth [2015], a 4-week-old pig is comparable to a 7-year-old child, and therefore data for a 21.3 kg pig were used to assign dielectric properties for the child model.

Setup and Computation Methods

Time-domain algorithms have been widely used in studies calculating the EM power absorbed within human models [Dimbylow, 1997; Dimbylow and Bolch, 2007; Findlay and Dimbylow, 2010; Hirata et al., 2010, 2012]. The time-domain solution approach is capable of handling inhomogeneous, dispersive, and lossy dielectric mediums such as those found within the human body. For geometries in which wave-object interaction has to be considered in open regions, the computational space has to be truncated by absorbing boundaries. Perfectly matched layer (PML) absorbing boundaries were used in order to minimize any undesirable artefactual reflections [Dimbylow, 1997; Chen et al., 1999; Sullivan, 2013].

Prior to inclusion of the antenna in the exposure model, a set of validation simulations was completed using plane incident waves with vertical polarization. Many studies have been conducted to calculate the plane wave exposure at various frequencies, as discussed in various recent studies [Dimbylow, 1997, 2002; Dimbylow and Bolch, 2007; Bakker et al., 2010; Findlay and Dimbylow, 2010; Hirata et al., 2012]. In this study, calculations were performed for a plane wave with the standing human model suspended in air in one of the scenarios. Dimbylow and Bolch [2007] found slightly higher values for the isolated case as compared to the grounded case above 1 GHz, where the plane wave was irradiating the isolated standing body from the front with the electric field (E-field) component aligned vertically.

Meshing and Stability Conditions

The FIT method (as with the FDTD method) follows the time evolution of a field interacting with body divided into voxels (grids). Selecting the largest cell size is dictated by the minimum computational stability requirement, which is generally governed by a minimum of 10 cells per wavelength within the highest permittivity region of the body [Dimbylow and Bolch, 2007; Sullivan, 2013]. The selection of cell sizes is also driven by the aim to provide satisfactory accommodation of the physical representation of the body and computation efficiency. The maximum mesh cell size was thus limited to 4.13 and 1.49 mm at GPT and ISM bands. The minimum mesh cell requirement for the modified NAOMI, NORMAN, and EARTHA models was therefore 28.84 million, 35.71 million, and 29.43 million mesh cells, respectively, based on the $xyz$ dimensions of the models.

Comparison With an Analytical Benchmark

A theoretical calculation model was used as a benchmark for validating the FIT/FDTD software. This theoretical model was used for expressing the EM field and SAR induced inside a lossy dielectric sphere by an incident plane-wave. The analytical solution was based on exposing single layered, muscle-equivalent model spheres, with radii of 3 cm and 15 cm, to the plane wave of 1,000 MHz radiation [Henry and Arthur, 1974]. Similar muscle dielectric properties were used for those in analytical and computational models [Schwan and Piersol, 1954].

Plots of normalized analytically assessed SAR variations along the major axes of a muscle-equivalent dielectric sphere (radius $= 3$ cm) are shown in Figure 7. The black solid lines show normalized analytically solved SAR trends along the three major axes $x$, $y$, and $z$ [Henry and Arthur, 1974]. Calculations are based on 1,000 MHz plane waves, with power flux density of 1 mW cm$^{-2}$ and WBSAR of 0.235 W kg$^{-1}$. For the convenience of presentation, the distributed SAR values are normalized to the maximum SAR given for each figure. It was found that strong standing wave “hot spots” exist in the sphere.

Similarly, the computed SAR patterns inside the 3 cm sphere using the CST MWS are also presented with colored lines in Figure 7. The SAR values have also been normalized to the maximum value in line with the mie-theory plot, for the purpose of comparison. The

![Fig. 7. Plots of normalized FIT/FDTD-computed SAR patterns along major axes of a muscle-equivalent dielectric sphere (Radius = 3 cm). Calculations are based on a plane wave source of 1,000 MHz, with energy flux density of 1 mW cm$^{-2}$, WBSAR = 0.241 W kg$^{-1}$](image-url)

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The computed WBSAR value is $0.241 \text{ W kg}^{-1}$ with power flux density similar to analytical solution ($1 \text{ mW cm}^{-2}$). An excellent correlation was observed between analytical predictions and FIT/FDTD (CST MWS) computations (Fig. 7). The difference between SAR values decreases progressively for the X, Y, and Z data sets; however, the results are in excellent agreement generally, thus providing validation for this method. An excellent correlation was observed with the overall estimated WBSAR, with the error in computational value estimated to be less than 3%.

Fig. 8. Plane wave exposure scenarios for models; (a) When standing on ground plane and exposed from front to back; (b) When sleeping without ground plane and exposed from top to bottom; where extra free space ($l/4$) is added around body with chosen PMLs.
Exposure Scenarios and SAR Calculations

The exposure of the models was analyzed at two different frequencies, 868 and 2,450 MHz. These frequencies correspond to SM antenna operating frequencies as described in previous sections. The separation distance between the antennas and model was initially set to a nominal value of 15 cm approximately, while the models were exposed to a plane wave in the far-field. Both standing and sleeping positions were considered for each model. For the standing position, the model was placed upright on a ground plane (Fig. 8a), and for the sleeping position, the model was placed above the ground, in a horizontal position mimicking the sleeping position on a bed (Fig. 8b). In all cases, all relevant SAR calculations were computed and the results are summarized in this paper.

Plane Wave Exposure of Models

Plane wave exposure on human models was used to mimic far-field conditions for sources located beyond 15 cm distance. Any distance greater than 15 cm between the human model and SM antenna devices is large in terms of the computational volume, and performing an assessment on human models would require a great amount of computation power. Therefore, plane waves were employed to realize exposure from far-field sources, utilising two different scenarios: when models are grounded and when models are isolated. Details of these plane wave exposure arrangements for the human models are given in the following sections.

Standing Models on a Ground Plane Exposed From Front to Back With Plane Wave

Calculations of the field exposure were performed for a plane wave irradiating the model from the front with the E-field component aligned vertically. In the numerical computation tool employed, excitation power was dependent on the boundary size in plane-wave exposure condition, since the models were excited by a plane wave peak E-field strength of 1 V/m over the entire simulation area. Moreover, the excited field was doubled due to the perfect electrical conductor (PEC) boundary at the bottom plane acting as a mirror for the E-field.

The peak E-field strength is presented as a root mean square (rms) value, which is 1.414 V/m rms using the formula $V_{\text{rms}} = 0.707 	imes V_{\text{pp}}$ [Reference Designer Calculator, 2015]. However, the peak power density is 2.65 m W/m$^2$ based on the assumption that 1 V/m is applied through free space (12/377). For PEC ground boundary, the peak power density becomes four times higher than that of free space, based on the assumption that 2 V/m (due to mirroring effect of PEC/ground) is applied through free space (22/377). Therefore, the peak power density of the grounded models is 10.61 mW m$^{-2}$. The WBSAR values calculated for the grounded models at both frequencies were well under the basic restriction level described by the ICNIRP guidelines, as shown in Figure 9a. The differences in WBSAR values mainly resulted from difference in average mass densities among the models.

When models were exposed to a plane-wave under grounded conditions and 10 g averaging method...
applied, few hot spots (regions of locally enhanced absorption) were identified, as shown in Figure 10. The most affected parts within the child model at both frequencies were found to be at the anterior and posterior shins. For NAOMI, the plane wave exposure condition led to most absorption in the wrist, ankle, nose, neck, and fingers. In the case of NORMAN, similar parts of the body were affected, but also the eyes, groin, and knees. The SAR distribution highlights the absorption maximum at thinner parts of the body, e.g., wrist, ankle as indicated above. This could be due to the resonances appearing in such parts of body. It is interesting to notice that NAOMI max. SAR values were higher than child in plane wave exposure cases. These findings are in line with the findings given in this publication [Piuzzi et al., 2011]. However, the SAR scale indicates that this effect was still negligible in comparison with guideline levels (Fig. 9b).

Isolated Models in Sleeping Position Exposed From Top to Bottom With Plane Wave

Calculations were performed for a plane-wave irradiating the model from the top with the E-field component aligned vertically under the isolated condition. In the case of isolation, the excitation E-field strength was set to a peak value of 1 V/m over the entire simulation area. Therefore, the peak power density of isolated models across the spectrum was 2.65 mW m\(^{-2}\). When the models were isolated in air in a sleeping position, the WBSAR values for both frequencies were well under the basic restriction given in the exposure guidelines, as shown in Figure 11a and b. The reasons behind the difference in max. SAR values are the same as explained in the above section. However, a few hot spots were identified at both frequencies 868 and 2,450 MHz. The maximum absorption regions for all three models are shown in Figure 12, but again in all cases the maximum 10 g averaged SAR is well below the limit value.

Model Exposures With SM Device Antenna

This section describes the exposures resulting from modeled SM devices, as opposed to plane waves. An SM antenna was modeled in a plastic box with 2 mm thick walls, in order to mimic the real device. The SAR values were normalized to an antenna output power of 1 W to allow for comparison with measured data described in the companion paper [Peyman et al., 2017]. It is worth mentioning that 1 W is in fact approximately 65 times higher than the maximum 15 mW power expected from SM devices during transmission. Moreover, the power density in all cases calculated from measuring in \(x\) and \(y\), \(x\) and \(z\), or \(y\) and \(z\) directions depends on the geometry of simulation box. After calculating the simulation box coordinates, area formulae were used to divide the output power by the calculated area in order to get the required power density in each scenario. The output powers from SM antenna at 868 and 2,450 MHz band were 0.7 W and 0.99 W, due respectively to the corresponding antenna radiating efficiency of 70% and 99%.
Due to the different voxel model sizes, boundary conditions (grounded or isolated), and exposure scenarios, the power density varied in each case. Therefore, for the standing position all three phantoms were modeled and assumed to be standing on ground with a distance between model and SM antenna set to 15 cm, as shown in Figure 13a. Similarly, for the sleeping position all three phantoms were modeled in a sleeping isolated position, with the distance between model and SM antenna set to 15 cm, as shown in Figure 13b.

Calculations were performed for an SM device antenna irradiating the grounded model from front side. When the models were grounded, the WBSAR values for both frequencies were well under the basic restriction level given in the guidelines, as shown in Figure 14, even though the output power from the modeled smart meter antennas were substantially above those from real devices.

![SAR distribution](image-url)  
*Fig. 11. SARs distribution resulting from plane wave exposure; (a) WBSAR; (b) Max. SAR (10 g); when models are under sleeping condition and exposed from top to bottom with 1V/m peak plane wave.*

**Standing Models on a Ground Plane Exposed From Front to Back**

Fig. 12. NAOMI, NORMAN, and Child Max. SAR (10 g) distribution at 868 MHz, when models are under sleeping condition and exposed from top to bottom with 1V/m peak plane wave.

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At both frequencies, when the models were exposed under grounded conditions, a few hot spots were observed, as shown in Figure 15. Because the height of a child model is smaller, when the SM device antenna was placed at 1-m height from the ground, the highest exposures were seen in the brain, eyes, and forehead, at both frequencies. For both NAOMI and NORMAN, the exposure was relatively higher in the stomach area at both frequencies. The female model showed higher WBSAR levels than the male model, as shown in Figure 14. This could be due to the different distances between the body and SM antenna in the respective models. The distance was measured from the middle of feet and was set to approximately 15 cm. The tummy regions of both models were also different in shape, so the differences in distance and body shape (especially in the tummy region) may explain the different SAR distributions (Fig. 15). In any case, the calculated SAR values were negligible in comparison with the ICNIRP guidelines.
Models in Sleeping Position Exposed From Top to Bottom

Calculations were performed for an SM device antenna irradiating the model from top when the model was in a sleeping condition. In this scenario, all the WBSAR values for both frequencies were well under the basic restriction level defined in the guidelines, as shown in Figure 16, even though the output power from the modeled smart meter antennas were substantially above those from real devices. A few hot
spots were identified in the skull at both frequencies, as shown in Figure 17. In all exposure situations, the highest SAR values occurred in the brain, nose, and eyes, similar to that of the plane wave exposure scenario.

DISCUSSION

Review on Numerically Calculated SAR

In this study, human models of three different age groups were assessed to determine the induced WBSAR.

Fig. 16. SAR distribution resulting from exposure close to SM antennas; (a) WBSAR; (b) Max. SAR (10 g); when models are under sleeping condition and exposed from top at 15 cm distance with 1W input power of SM antenna.

Fig. 17. NAOMI, NORMAN, and Child Max. SAR (10 g) distribution at 2,450 MHz, when models are under sleeping condition and exposed from top at 15 cm distance with 1W input power of SM antenna.
and maximum (10 g averaged) SAR distributions when exposed to radio signals typical of those from SM HAN sources. SAR distributions were assessed for 24 different scenarios, including standing and sleeping positions, when exposed at various distances from the signal source. Numerical simulations were carried out using validated and well-established computation tools, and through comparisons with similar configurations in earlier work [Dimbylow, 2002]. The exposure configurations utilized high-resolution human models, which allowed for age- and frequency-dependent tissue parameters. Dielectric properties of various tissues at different ages were assigned using a curve fitting technique applied to published measured data. Signal sources were simulated using realistic antenna designs to mimic the real sources at close distances, and plane waves to investigate far-field conditions of exposure.

The calculated WBSAR values in the present study were different from those published previously [Dimbylow, 2002]. This is attributed to the difference in excitation parameters where the E-field of the signal in the previous study was set to 1 V/m rms, whereas in this study it was set to 1 V/m peak value which is equivalent to 1.41 V/m rms. Therefore, the WBSAR values for the grounded, plane wave exposure in the standing position scenario were expected to be twice as high as those reported in Dimbylow [2002]. To confirm this, additional simulations were conducted on the NORMAN model standing on a grounded plane and exposed to a plane wave of 868 MHz. An excitation E-field strength of 1 V/m (rms) resulted in a WBSAR value of approximately 17 µW kg\(^{-1}\), which is in line with other reported results.

When the model was exposed to double the amplitude of the excitation E-field strength, i.e., 2 V/m (rms), the resulting WBSAR was approximately 69 µW kg\(^{-1}\), which is larger by a factor of four. This is due to the square of the doubled field, which is governed by the relationship \(|E|^2\). Similarly, when the plane wave was excited with an 868 MHz signal with a peak amplitude of 1 V/m, the peak field doubled in the presence of the metallic ground plane resulting in a field strength of 1.414 V/m (rms). In this case, the power increased by a factor of two compared to the first case, giving a WBSAR value of around 35 µW kg\(^{-1}\).

Similar differences were observed when the simulations were repeated at 2,450 MHz. Within the bounds of the various configurations considered, higher SAR values were always observed for the child model, compared with the adult models. This is attributable to differences in the dielectric properties and mass densities, which is in line with observations reported by Hurt et al. [2000].

Comparison Between Simulations and Measurements

Comparisons were also made in this study between the simulated and measured E-fields and power densities as described in the companion paper [Peyman et al., 2017] Also, the SAR values predicted from the measured power density levels were assessed under a pessimistic assumption of plane wave equivalence. For the purpose of simulations, a computational domain representing an anechoic chamber with dimensions of 3.6 m × 2.4 m × 2.4 m was designed similar to that used in the laboratory measurement setup [Peyman et al., 2017].

In free space, the E-fields and power density levels were calculated as a function of distance as shown in Figures 18 and 19. It is worth mentioning that the maximum output power used in simulations and measurements was as 1 W and 15 mW, respectively. After normalising the simulated power densities to levels similar to measured power densities, good agreement was achieved between simulated and measured power densities for a particular device. The power density measured from IHD02 (device under the test ID) at 50 cm and 1 cm distance was 1.13 mW m\(^{-2}\) and 0.32 mW m\(^{-2}\) respectively, whereas the simulated power density after normalization was 1.15 mW m\(^{-2}\) and 0.30 mW m\(^{-2}\) at 50 cm and 1 cm, correspondingly, as compared to measured power densities of IHD02 device. Measurements were performed on number of samples of smart meters provided by various manufacturers and utility company devices [Peyman et al., 2017]. Therefore, there

![Fig. 18. Comparison between simulated and measured E-Field from SM devices.](image)
was some difference among the power densities in simulations with respect to measurements.

Although all simulations were performed at 15 cm distance using the SM antenna model, SAR values beyond that distance were assessed using plane wave equivalent configurations as described in plane wave exposure section. Simulated SAR values were normalized with respect to simulated and measured power densities at 50 cm distance, as shown in Tables 2 and 3. These two tables depict the estimated WBSAR and maximum SAR (10 g) values, respectively, at the measured power density levels. The comparison between SAR values were restricted to maximum and average measured power density levels due to the large number of measurements on SM devices [Peyman et al., 2017].

The maximum power density measured in the laboratory was 13.72 mW m$^{-2}$ from CH06-3 (device under test ID) at a distance of 50 cm and in the 2,450 MHz band, with exception of one “outlier device (EM05)” that had a power density of 88.71 mW m$^{-2}$ [Peyman et al., 2017]. The power density calculated in the numerical assessment part was 10.61 mW m$^{-2}$ at 2,450 MHz, when models were exposed to a plane wave under standing configurations. The power density in simulations was calculated based on the size of bounding box which contains the voxel model. Therefore, the measured power density emitted from Comm-Hub device was found to be relatively higher as compared to simulations.

The results show that the energy deposition was distributed differently for each model, and this was due to differences in dimensions, frequency of interest, anatomical and dielectric properties, and exposure setup. The highest maximum SAR (10 g) values were observed when models were exposed to near field signals emitted from antennas operating at 868 and 2,450 MHz bands, in standing or sleeping position. In contrast and as expected, the highest WBSARs were observed when models were exposed to plane waves in standing or sleeping positions. The WBSAR value for NORMAN in standing position at 868 MHz was 34 μW kg$^{-1}$, falling to 29 μW kg$^{-1}$ at 2,450 MHz when exposed to a plane wave (see Fig. 9).

On the other hand, the WBSAR value for NORMAN, when exposed from SM antenna sources in standing position, was 0.87 μW kg$^{-1}$ and 0.82 μW kg$^{-1}$ at the former and later frequency bands.

### TABLE 2. Comparison Between WBSAR Values at 2,450 MHz Band From Simulated and Measured Power Density Levels at 50 cm Distance

| Models exposure condition | Simulated | Simulated Power Density (mW m$^{-2}$) | Normalized WBSAR to the input power density (μW kg$^{-1}$ per m$^{-2}$) | Measured power density (mW m$^{-2}$) | Predicted WBSAR (μW kg$^{-1}$) |
|--------------------------|-----------|--------------------------------------|-------------------------------------------------|---------------------------------|-------------------------------|
| Child standing           | 51.79     | 10.61                                | 4.88                                            | 88.71                          | 432.90                        |
| NAOMI standing           | 31.06     | 10.61                                | 2.93                                            | 88.71                          | 259.69                        |
| NORMAN standing          | 29.57     | 10.61                                | 2.79                                            | 88.71                          | 247.23                        |
| Child sleeping           | 6.84      | 2.65                                 | 2.58                                            | 88.71                          | 228.98                        |
| NAOMI sleeping           | 2.53      | 2.65                                 | 0.96                                            | 88.71                          | 84.69                         |
| NORMAN sleeping          | 2.58      | 2.65                                 | 0.97                                            | 88.71                          | 86.37                         |

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The differences were due to differences in power densities. The power density was relatively high in all SM antenna exposure configurations, mainly due to the relatively close distance (15 cm) considered in all SM antenna exposure conditions, which is considered to reflect a worst-case scenario.

Power densities were also calculated as a function of distance in both simulations and measurements where good agreement was achieved after normalization. The estimated SAR values calculated for the measured power density levels were well below the guidelines. As power density decreases, the SAR values generally follow the same falling trend. The 1 W peak input power assigned to the SM antenna substantially overestimated what SMs are likely to emit (15 mW maximum limit).

Overall, in both simulations and measurements the SAR levels were found to be very low in comparison with basic restriction levels advised by ICNIRP to protect human health. Similar observations were made in Health Canada [2011], where the exposure level from SM sources was found to much less than that resulting from mobile phones used in close proximity to the head for voice calls.

**CONCLUSION**

The simulations described in this paper demonstrate that the exposures incurred from SM devices produce WBSAR and max. SAR (10 g) values well below the exposure guideline limits. This was the case for all the exposure scenarios considered for all age groups, despite the overestimated emitted powers and the fact that continuously transmitted waves were used rather than the more realistic shorter duration signals that are characteristic of such devices.

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**TABLE 3. Comparison Between Maximum SAR Values at 2,450 MHz From Simulated and Measured Power Density Levels at 50 cm Distance**

| Models exposure condition | Simulated Max. SAR (mW kg⁻¹) | Simulated power density (mW m⁻²) | Normalized Max. SAR to the input power density (mW kg⁻¹ per W m⁻²) | Measured power density (mW m⁻²) | Predicted Max. SAR (mW kg⁻¹) |
|---------------------------|-----------------------------|---------------------------------|---------------------------------------------------------------|-----------------------------|-----------------------------|
| Child standing            | 0.73                        | 10.61                           | 0.07                                                         | 88.71                       | 5.93                        |
| NAOMI standing            | 0.80                        | 10.61                           | 0.07                                                         | 88.71                       | 5.93                        |
| NORMAN standing           | 0.50                        | 10.61                           | 0.05                                                         | 88.71                       | 5.93                        |
| Child sleeping            | 0.08                        | 2.65                            | 0.03                                                         | 88.71                       | 5.93                        |
| NAOMI sleeping            | 0.11                        | 2.65                            | 0.04                                                         | 88.71                       | 5.93                        |
| NORMAN sleeping           | 0.07                        | 2.65                            | 0.03                                                         | 88.71                       | 5.93                        |
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