Personal Distributed Exposimeter for Radio Frequency Electromagnetic Field Assessment

Arno Thielens[1], Hans De Clercq[2], Sam Agneessens[3], Jeroen Lecoutere[2], Leen Verloock[1], Frederick Declercq[3], Günter Vermeeren[1], Emmeric Tanghe[1], Hendrik Rogier[3], Robert Puers[2], Luc Martens[1], and Wout Joseph[1]
Department of Information Technology, Ghent University / iMinds, Ghent, Belgium
*Corresponding author e-mail: Arno.Thielens@intec.UGent.be

SHORT ABSTRACT

A personal distributed exposimeter (PDE) consisting of 3 radio frequency (RF) acquisition nodes is constructed using textile antennas and wearable electronics. Numerical simulations are used to design the PDE. Calibration measurements at 950 MHz, using a human subject, are performed in an anechoic chamber. Compared to conventional exposimeters, which only measure in 1 position on the body, an excellent 95% confidence interval of 7 dB on measured power (densities) and isotropy of 0.5 dB are measured.

INTRODUCTION

Radio Frequency (RF) exposimeters or personal dosimeters are devices used to assess the typical levels of exposure of a subject. They are currently used in several measurements of RF exposure [1,2,3]. The purpose of these devices is to measure the electromagnetic fields incident on the human body, which can be compared to international guidelines, such as those issued by ICNIRP [4]. However, when measuring the fields, these devices are faced with uncertainties due to absorption and reflection of the subject's body [5,6]. It can easily be understood that incident RF electromagnetic fields near the body will be heavily perturbed by the presence of the body and thus also the fields measured by an exposimeter. Moreover, the fields measured by current exposimeters appear to be dependent on the polarization of the incident electromagnetic fields [5]. An on-body worn personal distributed exposimeter (PDE), which consists of multiple RF sensor nodes worn on predefined, fixed positions on the body, is proposed in order to reduce the uncertainty and polarization dependence. The PDE uses lightweight wearable electronics and multiple textile antennas, which can both be integrated in a subject's clothes in order to maximize wearability. A first prototype of this PDE is designed, constructed, and calibrated at 950 MHz, the global system for mobile communication (GSM) downlink (DL) frequency.

MATERIALS AND METHODS

The PDE is based on finite-difference time-domain (FDTD) simulations using the Virtual Family Male (VFM) [7]. This is a heterogeneous adult phantom based on magnetic resonance imaging of a volunteer with a body mass index of 22.3 kg/m². The dielectric parameters assigned to the phantom's tissues come from the Gabriel database [8]. FDTD simulations are used to determine the electric fields at 1cm from the phantom's upper body under far-field exposure in a realistic multi path environment. The incident electromagnetic waves are generated using the method described in [6,9]. A linear regression model is developed to determine the incident root-mean-squared electric field ($\boldsymbol{E}_{RMS}^{free}$), using the electric fields recorded by the PDE ($\boldsymbol{E_{RMS,i}^{body}}$), with *i* the *ith* measurement point of a total of N sensors on the body:

$$E_{RMS}^{free} = b_0 + \sum_{i=1}^{N} b_i E_{RMS,i}^{body} \quad + err \tag{1}$$

With err the residual and b_i (i = 0..N) the regression coefficients. Using a step-wise algorithm, N locations on the body which cause the smallest average residual are selected as locations to deploy sensors on the body. The algorithm is constructed in such a way that the values of $\boldsymbol{E_{RMS,i}^{body}}$ take into account the polarization of the antennas used to record the electric fields. In this prototype, the number of sensors on the body N is chosen to be 3.

The RF sensors consist out of a textile antenna and an RF-exposure acquisition system. The used textile antenna is a quarter wavelength planar inverted F antenna (PIFA) [10] which covers the GSM 900 downlink band with a 60 MHz bandwidth. The RF-exposure acquisition system contains a receiver tuned to 950 MHz and a microcontroller for data management. The nodes communicate via IC2 with a central processing unit, which is connected to a laptop using USB. All antennas, nodes, electronics, and interconnections are lightweight and flexible in order to increase wearability [11].

A prototype of the PDE using 3 RF acquisition nodes placed on a human subject with a BMI comparable to that of the VFM ($\pm\mathbf{1}$ kg/m²) is calibrated in an anechoic chamber. The subject is rotated over ϕ from 0° to 360° under exposure of a dipole tuned at 950 MHz placed in his far-field. Each RF node (*i*) will record a certain power $\boldsymbol{P_{r,i}^{body}(\phi)}$**.** Using these powers an average measured response R_{meas} (dB) can be determined. The received powers are averaged over ϕ and divided by the received power of the antennas in free-space $\boldsymbol{P_r^{free}}$, averaged over the subject's rotation axis:

$$R_{meas} = 10 \times \log\left(\frac{\langle \frac{1}{N}\sum_{i=1}^{N} P_{r,i}^{body} \rangle_\phi}{P_r^{free}}\right) \tag{2}$$

$\boldsymbol{P_r^{free}}$(W) is directly related to the free-space power density $\boldsymbol{S^{free}}$(W/m²), which is the quantity one wants to measure with an exposimeter, through the antenna factor. The response R_{meas} is determined for two orthogonal polarizations of the dipole (TX): parallel to the subject rotation axis (vertical, $\boldsymbol{R_{meas}^{V}}$) and perpendicular to this axis (horizontal, $\boldsymbol{R_{meas}^{H}}$). The ratio between these two responses (I = $\boldsymbol{R_{meas}^{V}/R_{meas}^{H}}$) is called the isotropy and is a measure for the polarization dependence of the PDE.

RESULTS

Figure 1 shows the angular averaged measured response and its 95% confidence interval for the calibrated prototype of the PDE using the combination of 1, 2, and 3 RF sensors with the smallest 95% confidence interval. The average 95% confidence interval decreases as more sensors are considered and the isotropy improves as well. In the case where R_{meas} is averaged over all 3 sensors, the responses are -15.6 dB and -15.1 dB with a 95% confidence interval of 7 dB and 7.5 dB for the horizontal and vertical polarization of the dipole, respectively. This means that for example the 97.5% percentile ($p_{97.5}$) of R_{meas}^{H} is a factor 5 higher than the 2.5%

percentile ($p_{2.5}$). The measured isotropy using 3 sensors is determined to be 0.5 dB, which is excellent compared to a measured isotropy of 6.4 dB for commercial dosimeters at the same frequency, reported by Bolte et al. [5] and an isotropy in free-space (not measured on a human subject) of 2.1 dB reported in the manual of the EME SPY 140.

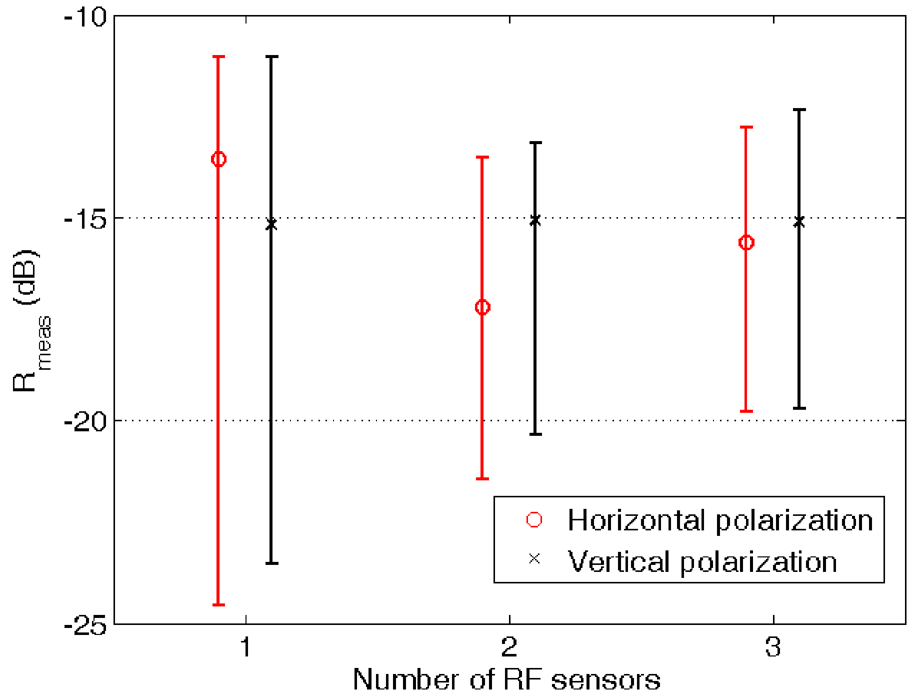

Figure 1: Angular averaged measured response (R_{meas}) and 95% confidence interval on this response for the calibrated prototype of the PDE using the combination of 1, 2, and 3 RF sensors with the smallest 95% confidence interval The error bars indicate the 95% confidence interval

Table 1 shows different estimations of the uncertainty on measurements using conventional dosimeters by different research groups in comparison with the uncertainty on measurements using this prototype of the PDE. Since not every study uses the same quantity to describe confidence intervals or uncertainty, three quantities are considered: 50% confidence interval (p_{75}/p_{25} (dB)), 90% confidence interval (p_{95}/p_{5} (dB)), and 95% confidence interval ($p_{97.5}/p_{2.5}$ (dB)). The PDE performs excellent in terms of all 3 different quantities in comparison with previous studies which estimate the uncertainty associated with measurements using a conventional dosimeter. Measurements using the PDE are several factors more accurate than those associated with conventional exposimeters, in particular the 95% confidence interval of the PDE is 11 dB and 15 dB smaller than the 95% confidence intervals estimated using numerical simulations and thus ideal circumstances with a static phantom and sensors that can record the exact root-mean-squared electric field considered in [11] and [6], respectively.

	50% confidence interval (dB)	90% confidence interval (dB)	95% confidence interval (dB)
Bolte et al. 2011[5]			
GSM900 DL V polarization (measurement)	6.5		
GSM900 DL H polarization	15.5		

(measurement)			
Neubauer et al. 2010[12]			
Multi path exposure at 946 MHz (simulation)	8.0	18	
Iskra et al. 2011[6]			
Multi path exposure at 900 MHz (simulation)			18.5
Thielens et al. 2013[11]			
Multi path exposure at 950 MHz (simulation)			22.5
Prototype PDE			
950 MHz H polarization (measurement)	4.5	7.0	7.0
950 MHz V polarization (measurement)	4.5	7.1	7.5

Table 2: Uncertainties on measurements and numerical simulations using an exposimeter reported in different studies.

CONCLUSIONS

A prototype of a personal distributed exposimeter (PDE) using 3 radio frequency measurement nodes is calibrated in an anechoic chamber on a real human subject with a BMI of 22±1 kg/m². The PDE shows an excellent average 95% confidence interval of 7 dB and an axial isotropy of 0.5 dB.

ACKNOWLEDGMENT

Wout Joseph and E. Tanghe are Post-Doctoral Fellows of the FWO-V (Research Foundation-Flanders). This research was funded by the Research Foundation – Flanders (FWO-V) under grant agreement No 3G004612.

REFERENCES

[1] Röösli M, Frei P, Bolte J, Neubauer G, Cardis E, Feychting M, Gasjek P, Heinrich S, Joseph W, Mann S, Martens L, Mohler E, Parslow RC, Poulsen AH, Radon K, Schüz J, Thuroczy G, Viel J, Vrijheid M. 2010. Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol. Environmental Health 2010, 9-23.

[2] Frei P, Mohler E. Neubauer G, Theis G, Burgi A, Frohlich J, Braun-Fahrlander C, Bolte J, Egger M, Roösli, M. 2009. Temporal and spatial variability of personal exposure to radiofrequency electromagnetic fields. Environmental Research (109):779–785.

[3] Bolte JFB, Eikelboom T. 2012. Personal radiofrequency electromagnetic field measurements in the Netherlands: Exposure level and variability for everyday activities, times of day and types of area. Environment International 48: 133-142.

[4] International Commission on Non-Ionizing Radiation Protection. 1998. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Physics 74: 494-522.

[5] Bolte J.F.B., Van der Zande G., Kamer J., 2011. Calibration and uncertainties in personal exposure measurements of radiofrequency electromagnetic fields. Bioelectromagnetics 32(8): 652-663.

[6] Iskra S, McKenzie R, Cosic I. 2010. Factors influencing uncertainty in measurement of electric fields close to the body in personal RF dosimetry. *Radiat Prot Dosimetry* 140 (1): 25-33.

[7] Christ A, Kainz W, Hahn EG, Honegger K, Zefferer M, Neufeld E, Rascher W, Janka R, Bautz W, Chen J, Kiefer B, Schmitt P, Hollenbach HP, Shen J, Oberle M, Szczerba D, Kam A, Guag JW, and Kuster N., The Virtual Family - development of surface-based anatomical models of two adults and two children for dosimetric simulations. Phys Med Biol 48:N23-N38, 2010.

[8] Gabriel C, Gabriely S, Corthout E. 1996. The dielectric properties of biological tissues. Phys Med Biol 41: 2231-2293.

[9] Vermeeren G, Joseph W, Olivier C, Martens L. 2008. Statistical multipath exposure of a human in a realistic electromagnetic environment, Health Physics 94: 345 − 54.

[10] Hertleer C, Tronquo A, Rogier H, Vallozzi L, Van Langenhove L. 2007. Aperture-Coupled Patch Antenna for Integration Into Wearable Textile Systems. IEEE Antennas and Wireless Propagation Letters 6: 392-395.

[11] Thielens A, De Clerq H, Agneessens S, Lecoutere J, Verloock L, Declerq F, Vermeeren G, Tanghe E, Rogier H, Puers R, Martens L, Joseph W. 2013. Distributed on Person Exposimeters for Radio Frequency Exposure Assessment in Real Environments. Submitted to Bioelectromagnetics.

[12] Neubauer G, Cecil S, Giczi W, Petric B, Preiner P, Fröhlich J, Röösli M. 2010. The association between exposure determined by radiofrequency personal exposimeters and human exposure: a simulation study. Bioelectromagnetics 31: 535-545.