CHAMPS ÉLECTROMAGNÉTIQUES :
DE LA DOSIMÉTRIE À LA SANTÉ HUMAINE

Dosimétrie en ondes millimétriques : problématiques, enjeux et solutions actuelles

Millimeter-wave dosimetry: current challenges and possible solutions

Maxim ZHADOBOV, Nacer CHAHAT*, Ronan SAULEAU*, Yves LE DREAN***

**Institut d'Électronique et de Télécommunications de Rennes (IETR), UMR CNRS 6164, Université de Rennes 1, Rennes, France (maxim.zhadobov@univ-rennes1.fr)*
*** Institut de Recherche sur la Santé, l'Environnement et le Travail (IRSET), Inserm U1085, Université de Rennes 1, Rennes, France (yves.le-drean@univ-rennes1.fr)*

Key words: millimeter waves, biocompatibility, 60-GHz body-centric communications, dosimetry, dielectric properties.

Summary

Due to the saturation of the lower part of the microwave spectrum and need in very high data rate transmissions, the operating frequencies of some professional wireless communication systems are now shifting towards the millimeter-wave frequency band. Following significant research efforts undertaken in the field of millimeter-wave electronics, several 60-GHz wireless communication technologies have already been introduced to the consumer market (e. g. WiHD, WiGig). The biocompatibility of millimeter-wave devices and systems is an important issue due to the wide number of possible body-centric wireless applications. In this paper, fundamentals about the millimeter-wave interactions with the human body are recalled. The available literature data on the dielectric properties of skin and biological solutions and recently developed experimental skin models in the 60-GHz band are summarized. Electromagnetic and thermal dosimetric aspects of an incident plane millimeter wave at the air / skin interface are considered. Finally, challenges and some recent developments in the field of numerical and experimental millimeter-wave dosimetry are drawn and discussed.

Introduction

Recent advances in millimeter-wave technologies have triggered an exponential interest to wireless applications at millimeter waves. Antennas and devices operating in this band have a reduced size compared to their counterparts in the lower part of the microwave spectrum. Furthermore, very high data rates (5 Gb/s, or even beyond) can be reached for short- or long-range communications. The 16 dB / km peak of oxygen-induced absorption around 60 GHz [1,2] makes this frequency range extremely attractive for secured local communications, particularly in indoor environments, guaranteeing low interference with other wireless services and devices, as well as between adjacent network cells. At the same time, because of this resonance absorption, human body has never been exposed to 57-64 GHz radiations in the natural environmental conditions.

60-GHz broadband short-range communications for Wireless Personal Area Networks (WPAN) have been promoted by the WirelessHD Interest Group and WiGig alliance. Current target market applications are mainly restricted to indoor wireless high-definition multimedia devices [3]. Integrated 60-GHz front-ends are expected to be commercialized by 2014 on lap tops. Moreover, recent progress in miniaturization and low-cost devices has triggered research activities aiming at developing future millimeter-wave body area networks (BAN). In such systems, the antennas might be placed directly on the body inducing localized exposures of the superficial body layers. Recently, several research groups have focused on the characterization of the body channel, development of on-body antennas, and integration with already existing devices [4-6].

Before being introduced to the market, millimeter-wave systems should comply with regulations that are usually based on the ICNIRP and/or IEEE exposure limits. For far-field exposures, the power density (PD) averaged over 20 cm^2 is limited to 1 mW/cm^2 (general public) and to 5 mW/cm^2 (workers) in the 60-GHz band [7,8]. To respect these limits and due to technological limitations, the typical power radiated by the radio front-ends is below 10 dBm. However, power densities up to 20 mW/cm^2 (general public) and 100 mW/cm^2 (workers) are permitted for local

exposure scenarios, i.e. for PD averaged over 1 cm^2 [7]. Exposures under these conditions have had a limited practical interest so far, but should now be studied in detail due to the expected development of body-centric communication systems [4,9,10]. In such systems, the antennas might be placed directly on the body inducing localized exposures of the superficial body layers.

In this context, it is fundamental to analyze millimeter wave / human body interactions from electromagnetic (EM) and thermodynamic viewpoints, as well as the potential biological consequences and their power thresholds. This paper makes an overview of the state-of-the-art in dosimetric evaluation of millimeter-wave interactions with the human body.

1. Fundamentals of the millimeter-wave interactions with the human body

1.1. Primary biological targets for millimeter waves

Two primary biological targets of 60-GHz radiations are the skin and eyes. Exposure of eyes leads to the absorption of the EM energy by the cornea characterized by a free water content of 75% and a thickness of 0.5 mm. Hereafter we will essentially consider the interactions with the skin as it covers 95% of the human body surface. From the EM viewpoint, the skin can be considered as an anisotropic multilayer dispersive structure made of three different layers, namely, epidermis, dermis, and subcutaneous fat layer. The skin also contains capillaries and nerve endings. It is mainly composed of 65.3% of free water, 24.6% of proteins, and 9.4% of lipids [11].

1.2. Major dosimetric quantities at millimeter waves

The main dosimetric quantities at millimeter waves are the following:

(1) ***Incident power density (PD)***, defined as

$$PD = \frac{P}{S} = \left| \vec{E} \times \vec{H} \right|, \tag{1}$$

where P is the incident power, S is the exposed surface area, and $\vec{E}$ and $\vec{H}$ are the electric and magnetic field vectors, respectively. This is the main exposure characteristic adopted by most of the international guidelines and standards in the 10-300 GHz frequency range.

(2) ***Specific absorption rate (SAR)***. The SAR is a quantitative measure of power absorbed per unit of mass and time. In contrast to the PD, it also takes into account the physical properties of exposed samples

$$SAR = \frac{P}{m} = \frac{\sigma \left| \vec{E} \right|^2}{\rho} = C \left. \frac{dT}{dt} \right|_{t=0}, \tag{2}$$

where m is the tissue mass, σ its conductivity, and ρ its mass density. C is the heat capacity, and T is the temperature. It is important to underline that in Eq. (2) σ combines both electrical and ionic conductivities.

(3) ***Steady-state and/or transient temperature (T)***, which is particularly important in case of medium- and high-power exposures.

2. Dielectric properties and experimental models

2.1. Dielectric properties of the skin and biological solutions at millimeter waves

The knowledge of the dielectric properties of the skin and biological solutions is essential for the accurate dosimetry. In contrast to frequencies below 20 GHz, existing data on the permittivity of tissues in the millimeter-wave band is very limited due to some technical difficulties. In the 10-100 GHz range, the dispersive dielectric properties of the skin and biological solutions are primarily related to the rotational dispersion of free water molecules. In particular, high losses are related to the free water relaxation with the peak at 19 GHz at 25°C [12].

The results of skin permittivity measurements reported in the literature so far have demonstrated strong dependence on the measurement technique and skin model (*in vivo* or *in vitro*, skin temperature, location on the body and thicknesses of different skin layers) (Table 1). Gabriel *et al*. [13] reported extrapolated complex permittivity of human skin up to 110 GHz based on measurements performed below 20 GHz. The results presented by Gandhi *et al*. at 60 GHz [14] were obtained using a Debye's model based on measurements performed for the rabbit skin at 23 GHz. Alabaster *et al*. [15] measured the complex permittivity of excised human skin samples at millimeter waves using a free-space technique. Hwang *et al*. [16] completed *in vivo* measurement on human skin up to 110 GHz using a coaxial probe. Alekseev *et al*. [17] carried out reflection measurement with an open-ended waveguide and proposed a homogeneous and multilayer human skin models fitting the experimental data. Chahat *et al*. recently reported results of direct measurements up to 60 GHz using a slim coaxial probe [18]. Based on these results, an improved broadband Cole-Cole model was proposed for several locations on the arm, namely at the palm, wrist, and forearm. The same research team has recently introduced a new method for determining dielectric properties of skin and phantoms at millimeter waves based on heating kinetics [19]. These data are compared with the theoretical values obtained using Maxwell's mixture

equation in Table 1 [20]. Significant discrepancies among the reported data are found for the real (11%) and imaginary (62%) parts (Gabriel's model is used as a reference).

Our team has recently reported the permittivity data for several biological solutions in the 2-67 GHz range [21]. The direct measurements have been carried out using a slim open-ended coaxial probe. The results have been obtained for several representative monomolecular solutions of proteins, amino acids, nucleic acids, and carbohydrates are analyzed and compared. Furthermore, measurements have also been performed for complex biomolecular solutions, including bovine serum albumin (BSA)–DNA–glucose mixture, culture medium, and yeast extract solution. In particular, our experimental data clearly show that free water permittivity can be used for modeling low-concentration biological solution (e.g. culture medium) above 20 GHz.

Table 1
OVERVIEW OF THE SKIN ELECTRICAL PROPERTIES AT 60 GHZ.

Reference	ε^*	Method
Gabriel [13]	7.98-j10.90	E[1]
Gandhi [14]	8.89-j13.15	E
Hwang [16]	8.05-j4.13	M[2]
Alabaster [15]	9.9–j9.0	M
Alabaster [15]	13.2–j10.3	E
Alekseev [17]	8.12-j11.14	M
Chahat [19]	8.31-j10.76	M
Mixture eq. [20]	9.38-j12.49	T[3]

[1]E=Extrapolation. [2]M=Direct measurement. [3]T=Theoretical value.

2.2. Experimental models of the skin in the 60-GHz band

To measure the power absorption in the body due to the exposure to millimeter waves, it is necessary to develop appropriate tissue-equivalent phantoms because direct measurements of the energy absorption induced in real human bodies are very challenging and involve some ethical issues. Furthermore, the experimental results might fluctuate due to the morphological inter-individual differences and variations of the dielectric properties of biological tissues, inducing thereby reproducibility problems.

Most of the existing narrow- and broad-band experimental phantoms are limited to 10 GHz [22-25]. Recently, we have developed the first millimeter-wave experimental phantom to mimic accurately the dielectric properties of the human body surface in the 55-65 GHz range [26]. This opens some new possibilities for the future millimeter-wave dosimetry studies, as well as for the on-body antenna measurements and propagation of the body-centric propagation channel [5].

3. Incident plane wave at the air / skin interface

3.1. Reflection and transmission

The skin dielectric properties have a significant influence on the reflection and transmission at the air/skin interface. Their variability (see Section 2.1) should be carefully taken into account for accurate dosimetric evaluations. For a 60-GHz plane wave illuminating a homogeneous semi-infinite flat skin model, the analytically calculated reflection and transmission coefficients are represented in Fig. 1 for the perpendicular polarization ($\vec{E}$ perpendicular to the plane of incidence) and parallel polarization ($\vec{E}$ parallel to the plane of incidence). As expected, the reflected power strongly depends on the angle of incidence and polarization. For normal incidence, 30-40% of the incident power is reflected from the skin.

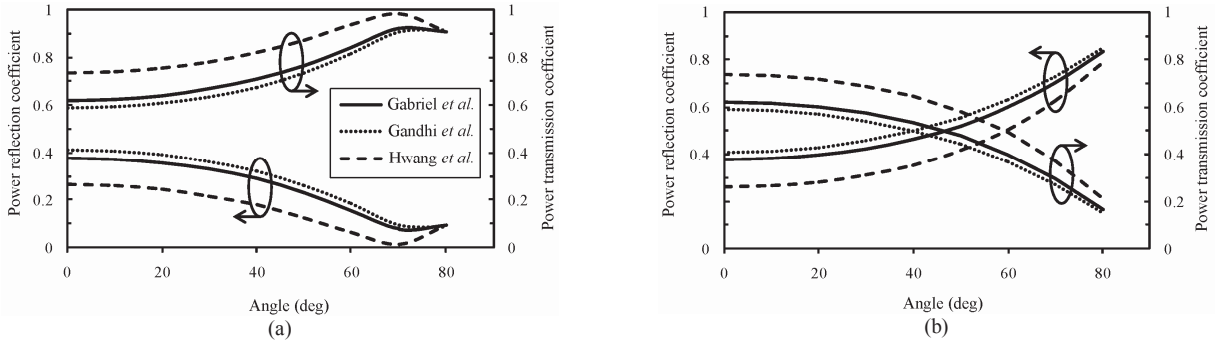

Fig. 1. Power reflection and transmission coefficients at the air/skin interface at 60 GHz for (a) parallel polarization, (b) perpendicular polarization.

3.2. Absorption

The transmitted power decreases exponentially in the skin as a function of depth. The attenuation of the PD and SAR at 60 GHz are plotted in Fig. 2. The PD and SAR are maximal at the skin surface. 40% (for Gabriel and Gandhi models) and 60% (for Hwang model) of the incident power reaches dermis; only 0.1% (for Gabriel and Gandhi models) and 10% (for Hwang model) reaches the fat layer. These results suggest that only epidermis and dermis should be considered for the EM dosimetry and on-body antenna characterization. This conclusion was confirmed by detailed analysis performed by Alekseev *et al.* for multilayer skin models [27].

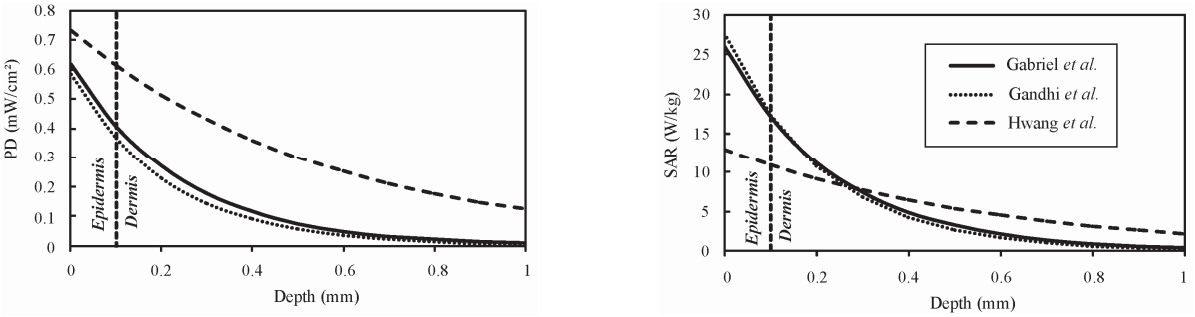

Fig. 2. Attenuation of the PD and SAR in the skin for an incident PD of 1mW/cm² at 60 GHz.

3.3. Heating

Shallow penetration depth of 60-GHz radiations in the skin (typically 0.5 mm) results in SAR levels that are significantly higher than those obtained at microwaves for identical PD values. This may lead to a significant heating, even for low-power exposures. The steady-state distribution of the relative temperature increments for a PD of 1 mW/cm^2 and 5 mW/cm^2 is represented in Fig. 3. These results correspond to the analytical solution of the 1-D heat transfer equation that takes into account the effect of surface cooling and blood flow. It is worthwhile to note that the heating is strongly correlated with the coefficient characterizing the heat transfer from the skin to air. These results demonstrate that heating due to local millimeter-wave exposure affects not only skin, but also subcutaneous tissues including fat and muscles. Therefore, a multilayer model should be used for the accurate assessment of the thermal effects.

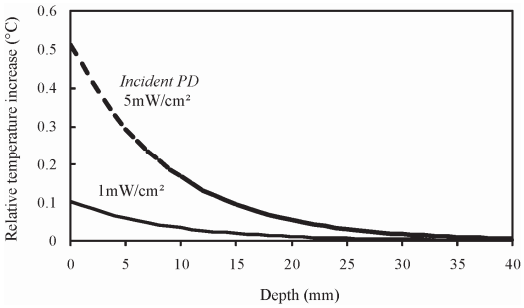

Fig. 3. Temperature increments for a homogeneous skin model exposed to a plane wave at 60 GHz.

The parametric study performed by Kanezaki *et al.* demonstrated that the temperature distribution induced by a millimeter-wave exposure strongly depends on the geometrical and thermal properties of the multilayer model [28]. Furthermore, Alekseev *et al.* demonstrated that heating is related to the blood flow in the skin, i.e. to the environmental temperature and physiological conditions [29,30]. It was shown that depending on these parameters steady-state temperature increments may vary by a factor of 3.

Finally, it is important to underline that, for typical exposure under far-field conditions, temperature increments induced by the PD below current international exposure limits are much lower than environmental thermal fluctuations.

4. Millimeter-wave dosimetry

Dosimetry studies have to be conducted to control and characterize the exposure levels within the samples and to optimize the exposure conditions (uniformity of the field distribution, number of simultaneously exposed samples, etc.). Two complementary approaches have been implemented.

4.1. Numerical dosimetry

The methodologies used for the numerical dosimetry at millimeter waves are essentially the same as those generally used at microwaves. However, several additional challenges appear due to the shifting towards shorter wavelengths: (*i*)

electrically large problems (λ_{skin} varies from 2.5 mm to 1.25 mm in 30-100 GHz range; this implies small mesh cell sizes of the numerical models - in the order of 0.1 mm [31,32]), (*ii*) uncertainties on the precise values of the dielectric properties of tissues and absence of well-established database beyond 20 GHz (see Section 2.1), and (*iii*) multi-scale problems related to the presence of the electrically small sub-structures (e.g. cell monolayers or different layers of skin). Furthermore, the EM problem should be coupled with the thermodynamic one to carefully take into account possible heating and dielectric constant variations related to the thermal gradients [33]. Significant changes of permittivity values of biological tissues and solutions typically appears for the temperature gradients $\Delta T>3°C$. FDTD, FEM, and FIT have been successfully applied for the numerical dosimetry studies [20,34].

4.2. Experimental dosimetry

At millimeter waves, the direct field-based dosimetry faces two major problems. First, the gradients of PD and SAR values within biological tissues are high because of the strongly localized absorption. This implies that the measurements should have spatial resolution better than 0.1-0.2 mm. Second, the already-existing *E*-field probes are too large in size for the local dosimetry, and additionally may perturb the EM field and temperature distribution. Furthermore, the sample conductivity should be known to determine the local or average SAR. Therefore, this experimental technique has a limited practical interest.

An alternative solution consists in remotely or invasively measuring the near-surface thermal dynamics of the sample under test (Eq. 2). This is the most efficient way to experimentally determine the SAR and temperature distributions. Some non-perturbing techniques have been reported for the simultaneous determination of T and SAR, including optical fiber measurements [32], high-resolution infrared imaging [20], and utilization of thermosensitive liquid crystals [35]. In particular, infrared radiometry in combination with micro-encapsulated thermosensitive liquid crystals was efficiently used for the EM and thermal dosimetry of rabbit and primates eyes [36]. For the animal and human studies, significant efforts have been undertaken by Alexeev *et al*. to supply accurate analytical, numerical, and experimental dosimetry [27,29,30,37].

5. Conclusions

This paper presents recent results in the field of the millimeter-wave dosimetry. The data available on the dielectric properties of skin at 60 GHz have been summarized; they demonstrate that a well-established permittivity database is missing for the millimeter-wave band. It is shown that 26-41% of power is reflected at the air/skin interface for the normal incidence, and this value deviates significantly for illuminations under oblique incidence. More than 90% of the transmitted power is absorbed by the skin, and therefore single- or multi-layer skin models are sufficient for the reliable EM dosimetry. Millimeter waves induce steady-state temperature increments of the order of several tenths of °C for PD below the current far-field exposure limits; however significant thermal effects may appear for local near-field exposures. It was demonstrated that, in contrast to the EM model, it is crucial to consider multi-layer structures including skin, fat, and muscle for the reliable thermal dosimetry. The state of the art in the numerical and experimental millimeter-wave dosimetry has been also discussed.

6. Acknowledgements

This work was supported by Agence Nationale de la Recherche (ANR), France, under ANR-09-RPDOC-003-01 grant (Bio-CEM project) and by "Centre National de la Recherche Scientifique (CNRS)", France.

References

[1] A. W. Straiton. The absorption and reradiation of radio waves by oxygen and water vapor in the atmosphere. *IEEE Trans. Antennas Propagat.*, 23, pp. 595-597, 1975.
[2] P. W. Rosenkranz. Shape of the 5 mm oxygen band in the atmosphere. *IEEE Trans. Antennas Propagat.*, 23, pp. 498-506, 1975.
[3] R. C. Daniels, J. N. Murdock, T. S. Rappaport, R. W. Heath. 60 GHz Wireless: Up Close and Personal. *IEEE Microwave Magazine*, 11, pp. 44-50, 2010.
[4] P. Hall. Advances in antennas and propagation for body centric wireless communications, *Europ. Conf. Antennas Propag. (EuCAP 2010)*, Barcelona, Spain, Apr. 12-16, 2010.
[5] N. Chahat, M. Zhadobov, R. Sauleau. On-body characterization of a wearable millimeter-wave antenna for body-centric applications. *33rd Annual Meeting of BEMS*, Halifax, Canada, Jun. 2011.
[6] N. Chahat, M. Zhadobov, R. Augustine, R. Sauleau. From human skin permittivity measurements up to 65 GHz to development of skin-equivalent phantoms for body-centric applications. *33rd Annual Meeting of BEMS*, Halifax, Canada, Jun. 2011.
[7] ICNIRP. Guidelines for limiting exposure to time varying electric, magnetic, and electromagnetic fields (up to 300 GHz). *Health Phys.*, 74, pp. 494–522, 1998.
[8] IEEE standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3kHz to 300GHz. *IEEE Std. C95.1*, 2005.
[9] S.-Q. Xiao, M.- T. Zhou, and Y. Zhang. Millimeter wave technology in wireless PAN, LAN, and MAN. CRC Press, 2008.
[10] P. Smulders. Exploiting the 60 GHz band for local wireless multimedia access: prospects and future directions. *IEEE Communications Magazine*, 40, pp. 140-147, 2002.

[11] F. A. Duck. Physical Properties of Tissue. Bath, U.K.: Academic, ISBN 0122228006, 1990.

[12] W. J. Ellison. Permittivity of pure water, at standard atmospheric pressure, over the frequency range 0–25THz and the temperature range 0–100°C. *J. Phys. Chem. Ref. Data*, 36, pp. 1–18, 2007.

[13] S. Gabriel, R. W. Lau, C. Gabriel. The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz. *Phys. Med. Biol.*, 41, pp. 2251-2269, 1996.

[14] O.P. Gandhi, A. Riazi. Absorption of millimeter waves by human beings and its biological implications. *IEEE Trans. Micro. Theo. Tech.*, 34, pp. 228–235, 1986.

[15] C. M. Alabaster. Permittivity of human skin in millimetre wave band. *Electronics Letters*, 39, pp. 1521–1522, 2003.

[16] H. Hwang, J. Yim, J.-W. Cho, C. Cheon, Y. Kwon. 110 GHz broadband measurement of permittivity on human epidermis using 1 mm coaxial probe. *IEEE Int. Micro. Symp. Digest*, 1, pp. 399–402, 2003.

[17] S. I. Alekseev, M. C. Ziskin. Human skin permittivity determined by millimeter wave reflection measurements, *Bioelectromagnetics*, 28, pp. 331–339, 2007.

[18] N. Chahat, M. Zhadobov, R. Augustine, and R. Sauleau. Human skin permittivity models for millimetre-wave range. *Electronics Letters*, 47(7), pp. 427 - 428, 2011.

[19] N. Chahat, M. Zhadobov, R. Sauleau, and S. I. Alekseev. New method for determining dielectric properties of skin and phantoms at millimeter waves based on heating kinetics. *IEEE Transactions on Microwave Theory and Techniques*, 2011 (in press, available online).

[20] M. Zhadobov, R. Sauleau, Y. Le Dréan, S. I. Alekseev, M. C. Ziskin. Numerical and experimental millimeter-wave dosimetry for in vitro experiments. *IEEE Trans. Microwave Theory Tech.*, 56, pp. 2998–3007, 2008.

[21] M. Zhadobov, R. Augustine, R. Sauleau, S. Alekseev, A. Di Paola, C. Le Quément, Y. Soubere, and Y. Le Dréan. Complex permittivity of representative biological solutions in the 2-67 GHz range. *Bioelectromagnetics*, 2012 (in press, available online).

[22] MCL-T broadband tissue equivalent liquid: 30 MHz to 6 GHz. available online at http://www.mcluk.org/pdfs/bbl.pdf.

[23] K. Ito, K. Furuya, Y. Okano, and L. Hamada. Development and characteristics of a biological tissue-equivalent phantom for microwaves. *Electron. Commun. Japan*, 84(4), pp. 67–77, 2001.

[24] T. Takimoto, T. Onishi, K. Saito, M. Takahashi, S. Uebayashi, and K. Ito. Characteristics of biological tissue equivalent phantoms applied to UWB communications. *Electron. Commun. Japan*, 90(5), pp. 48–55, 2007.

[25] J. Yonebayashi, S. Takamatsu, K. Saito, M. Takahashi, and K. Ito. Development of dynamic phantom for evaluation of breath detection doppler radar. *32nd Annual Meeting of BEMS*, Seoul, Korea, Jun. 2010.

[26] N. Chahat, M. Zhadobov, S. I. Alekseev, and R. Sauleau. Human skin-equivalent phantom for on-body antenna measurements in the 60-GHz band. *Electronics Letters*, 48 (2), pp. 67 - 68, 2012.

[27] S. I. Alekseev, A. A. Radzievsky, M. K. Logani, M. C. Ziskin. Millimeter-wave dosimetry of human skin. *Bioelectromagnetics*, 29, pp. 65–70, 2008.

[28] A. Kanezaki, A. Hirata, S. Watanabe, H. Shirai. Parameter variation effects on temperature elevation in a steady-state, one-dimensional thermal model for millimeter wave exposure of one- and three-layer human tissue. *Phys. Med. Biol.*, 55, pp. 4647–4659, 2010.

[29] S. I. Alekseev, M. C. Ziskin. Influence of blood flow and millimeter wave exposure on skin temperature in different thermal models. *Bioelectromagnetics*, 30, pp. 52–58, 2009.

[30] S. I. Alekseev, M. C. Ziskin. Millimeter-wave absorption by cutaneous blood vessels: a computational study. *IEEE Trans. Biomed. Eng.*, 56, pp. 2380–2388, 2009.

[31] M. Zhadobov, Ch. Nicolas Nicolaz, R. Sauleau, F. Desmots, D. Thouroude, D. Michel, Y. Le Dréan. Evaluation of the potential biological effects of the 60-GHz millimeter waves upon human cells. *IEEE Trans. Antennas Propag.*, 57, pp. 2949–2956, 2009.

[32] M. Zhadobov, R. Sauleau, R. Augustine, C. Le Quément, Y. Le Dréan, and D. Thouroude. Near-field dosimetry for in vitro exposure of human cells at 60 GHz. *Bioelectromagnetics*, 33, pp. 55-64, 2012.

[33] M. Cueille, A. Collin, C. Pivain, P. Leveque. Developement of a numerical model connecting electromagnetism, thermal and hydrodynamics in order to analyse in vitro exposure system. *Annals of Telecommunications*, 63, pp. 17-28, 2008.

[34] J. X. Zhao, Z. Wei. Numerical modeling and dosimetry of the 35mm petri dish under 46GHz millimeter wave exposure. *Bioelectromagnetics*, 26, pp. 481–488, 2005.

[35] Y. Suzuki et al. Experimental analysis on the thermal convection of aqueous humor in anterior chamber driven by the millimeter-wave exposure at 77GHz, *Annual Meeting of BEMS*, Seoul, June 14-18, 2010.

[36] H. A. Kues, S. A. D'Anna, R. Osiander, W. R. Green, J. C. Monahan, Absence of ocular effects after either single or repeated exposure to 10mW/cm^2 from a 60GHz CW source. *Bioelectromagnetics*, 20, pp. 463-473, 1999.

[37] S. I.Alekseev, O. V. Gordiienko, M. C. Ziskin. Reflection and penetration depth of millimeter waves in murine skin. *Bioelectromagnetics*, 29, pp. 340–344, 2008.