Comparison of temperature elevation between in physical phantom skin and in human skin during local exposure to a 28 GHz millimeter-wave

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***Abstract*—A millimeter-wave (MMW) at 28 GHz band, a candidate frequency for 5th generation wireless systems (5G), causes some concern about possible adverse effects on the human body. To investigate biological effects of local exposure to MMW, exposure systems equipped with a newly lens antenna, that can irradiate focused beam, were developed and characteristics of exposure for the skin were evaluated. The basic exposure performance of the systems was evaluated using temperature monitoring in physical phantom simulated human's skin and actual skin of forearm. Local temperature elevations were observed in both exposed skins, meaning achievement of results we expected in dosimetry. However, the time courses of these elevations were significantly different. These results suggest that some elements related to the temperature control such as heat conductivity and cooling by skin blood flow should be considered.**

Keywords— human exposure; Safety guideline; millimeter-wave; biological effects; phantom

I. INTRODUCTION

Mobile radios are now being used in various environments. With regards to the electromagnetic compatibility of such radio terminals, one of the most important issues is to develop accurate and reliable methods for estimating the interactions between electromagnetic fields (EMFs) and biological tissues. A basic metric used as the reference value of biological effects on high frequency (HF) - and microwave frequency (MW) - bands is specific absorption rate (SAR). The International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronic Engineers (IEEE) have separately issued advice notices [1]-[3]. In Japan, a telecommunications technology council report also included advice [4]. These guidelines are based on established adverse biological effects for human exposure to electromagnetic fields and include safety margins.

While recent expanding use of millimeter-wave (MMW), such as 5th generation wireless systems (5G) and WiGig (IEEE 802.11ad), is progressing, experimental and numerical studies is required to establish safety guidelines considering the action on living organisms due to millimeter-wave exposure [5]-[10]. However, due to the difficulty of apparatus for high duty exposure set-up on MMWs, only a few experimental studies have been reported. It is important to obtain reliable experimental data that can contribute to the study of biological effects exposed to MMW.

This paper presents development of a exposure equipment to perform experimental studies on thermal thresholds of biological effects under exposure to 28 GHz band MMW that is 5G candidate frequency band. The MMW exposure equipment that uses beam focusing technique was newly developed. To achieve high duty exposure at 28 GHz on skin of living body, we designed a dielectric lens of antenna that can irradiate focused beam on required exposure area (target area). To obtain exposure performance of the equipment, the authors developed physical phantom that simulates human's skin, and measured changes in temperature at the target area of phantom surface under MMW exposure. Furthermore, these temperature elevations in the phantom were compared with those in actual skin of human body.

II. DEVELOPMENT OF 28 GHZ BAND EXPOSURE EQUIPMENT

A. Overview of experimental studies on thermal thresholds of biological effects exposed to MMW frequency band

The main purpose of this research was to investigate the thermal thresholds of biological effects on real human body under exposure to MMW frequency band using dose responses of various physiological indices. Overview of the experimental studies for the detection of thermal thresholds under local

MMW exposure is shown in Fig. 1. Here, while radio wave at MMW band was exposed to the actual skin of human forearm, and some biological reactions were measured with high accuracy. The experiment was carried out in an artificial climate room that can manage temperature and humidity. Required conditions and main requirements for the MMW exposure set-up were as follows;

1) To realize highly localized radio wave exposure in predetermined area with desired power density on the skin of the human arm at the desired frequency

2) To keep enough space between the human body and the exposure device for setting of biological data measurement system and infrared thermography (Fig.1) in order to measure temperature rise and biological reactions at the same time during the MMW exposure.

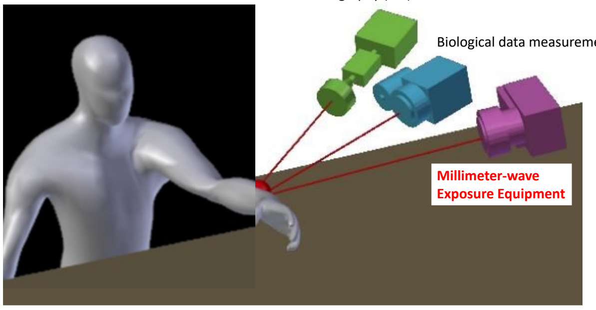


Fig. 1. Overview of experimental studies on thermal thresholds of biological effects under exposure to MMW.

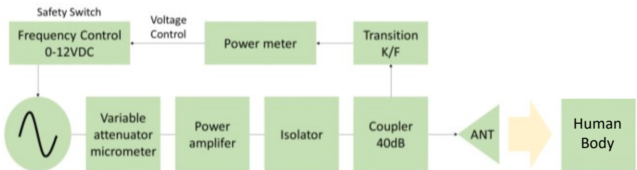


Fig. 2. Designed block diagram of the exposure set-up

3) Exposure shall be stopped safely in the case of an unexpected situation such as equipment malfunction.

Based on these requirements and some biological reaction phenomenon, we designed specifications for the 28 GHz exposure set-up construction, as summarized in Table I [11].

TABLE I. SPECIFICATIONS FOR DEVELOPED EXPOSURE SET-UP

Exposure Frequency [GHz]	28 +/- 1
Focal length [mm]	300
Diameter of focused exposure area (@-3 dB) [mm]	20
Achievable Power Density on the exposure area [W/ m^2]	0 - 50

B. Development of Exposure Set-up

Figure 2 shows designed block diagram of the exposure set-up. Here, we had to develop antenna that can irradiate focusing beam and decided using dielectric lens antenna in order to achieve the above specifications of focal length and diameter of exposure area at 28GHz as shown in Fig. 3.

C. Lens Antenna for High Focusing Exposure

The lens antenna was made of PTFE (polytetrafluoroethylene) material and designed the shape as to irradiate required focusing beam on the desired exposure area. In order to confirm radiation characteristics, electromagnetic fields excited by the lens antenna was simulated using FDTD method [12]. Figure 4 shows the numerical model and simulation results of electric field distributions. From the results, we confirmed the diameter of focused exposure area was achieved as we expected at the focused point.

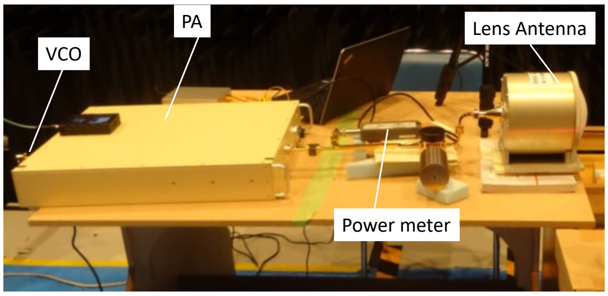
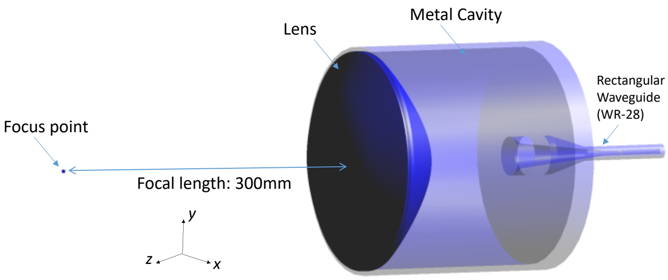
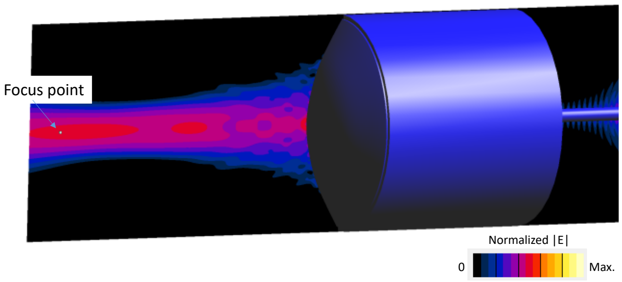


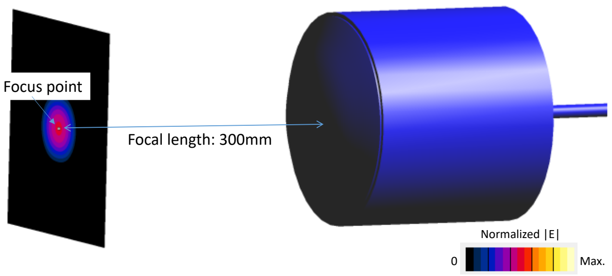
Fig. 3. Overview of 28 GHz exposure set-up



(a) Numerical model of the lens antenna



(b) |E|-field distribution (yz- plane)



(c) |E|-field distribution (xy-plane at the focused point)

Fig. 4. Radiation characteristics of the developed exposure set-up (FDTD simulation)

III. Development of 28 GHz Band Solid Phantom

A solid phantom material composed of carbon nanotubes, silicone rubber and carbon black, was developed in order to evaluate basic performance of the developed 28 GHz-band exposure set-up. By using the phantom, it was confirmed that the exposure set-up met required specifications. The carbon nanotubes took the form of cylindrical carbon molecules, with at least one end capped with a hemisphere of the structure. The diameter of a carbon nanotube was of the order of a few nanometers, and it was up to several micrometers in length. Carbon black was a form of amorphous carbon that had an extremely high surface area to volume ratio. By using these carbon materials mixed within silicone rubber, an arm shaped human skin phantom at 28 GHz band was achieved. The complex permittivity of this phantom material was controlled by changing the composition ratio of carbon nanotubes and carbon black within the silicone base. The penetration depth of the MMW in biological tissue was very small, and it became approximately 0.9 mm at 28 GHz band. Therefore, the target value of dielectric properties of the phantom was defined as averaged value of skin tissues and those are summarized in Table II. However, development of the phantom with the target value of dielectric properties is known to be technically difficult. In addition, errors occur when measuring the dielectric properties of the developed phantom. Therefore, we allowed an error within ±100% in difference between the target value and the measured one.

TABLE II. Dielectric Properties of skin tissues[13]

Skin Dry	
Relative permittivity	16.6
Conductivity [S/m]	25.8
Loss tangent	1.0
Skin Wet	
Relative permittivity	18.7
Conductivity [S/m]	26.2
Loss tangent	0.9

Figure 5 and 6 show the developed arm shaped human skin phantom and measured results of dielectric properties, respectively. The phantom consisted of homogeneous skin simulated material. The measured dielectric properties of the phantom was within the ±100% of the target values and it was acceptable for our experiments.

IV. Measurements of Temperature rise Characteristics using Skin Phantom and Real human body

In order to confirm performance of the constructed exposure set-up, we achieved measurement of the temperature rise characteristics using the developed phantom and real human's skin. Figure 7 shows an overview of the measurement of temperature rise characteristics using arm shaped skin phantom. Surface of the phantom was set on the focusing area of the exposure set-up. The developed exposure set-up allowed to control the antenna input power in order to suit for exposure dose condition required by examiner of each biological effects. Figure 8 shows an exemplar result of characteristics of temperature rise on the phantom surface using infrared thermography. In these measurements, the antenna input power was set to be 15 W and temperature of the phantom surface increased approximately 8 degrees Celsius after 60 sec. exposure.

Fig. 5. Overview of developed human arm-shaped phantom.

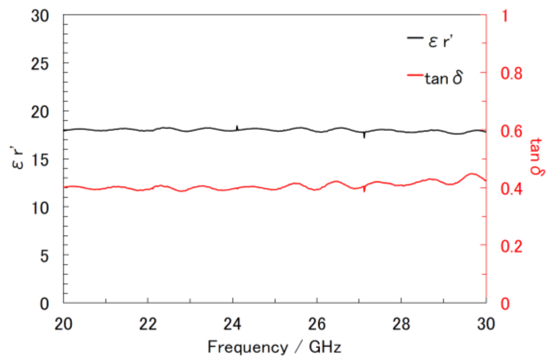


Fig. 6. Measurement result of relative permittivity and loss tangent of the human arm-shaped phantom.

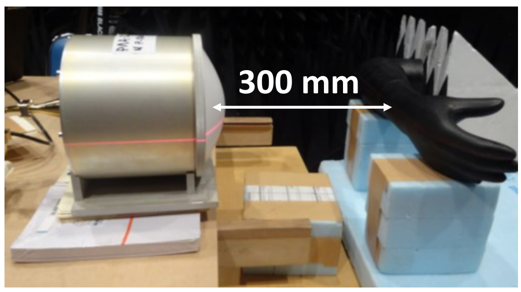


Fig. 7. Exposure set-up and arm-shaped phantom

Fig. 8. Measured result of temperature rise after 60 sec. irradiation. (Antenna input power : 15 W, measured by infrared thermography)

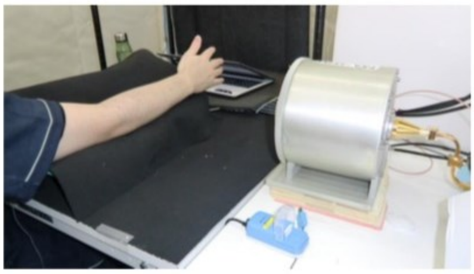


Fig. 9. Overview of measurement using real human body.

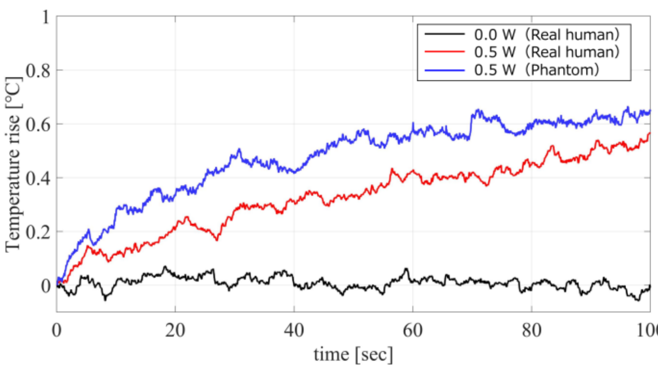


Fig. 10. Measured temperature rise characteristics of real human body and the phantom. (Antenna input power : 0 W and 0.5 W for real human body. 0.5 W for phantom)

In addition, the figure of temperature distribution clearly shows desired exposure at the target area of the phantom surface can be achieved.

Next, characteristics in temperature rise for real human body was evaluated, as shown in Fig.9. This experiment was carried out in an artificial climate room and managed temperature and humidity were 27 degrees and 50 %, respectively. Figure 10 shows the measured results of temperature increase characteristics on the real human body surface compared to the measurement result using the phantom. The target temperature in the phantom was always higher than that in the human skin through the MMW exposure of 100 sec. One of the reasons of these differences is due to the values of specific heat and thermal conductivity of each. In addition, cooling effects due to cutaneous microcirculation might be induced in actual skin surface.

V. Conclusions

This paper introduced newly developed exposure set-up for studies on biological effects of human exposed to millimeter-wave at 28 GHz band, that is 5th generation wireless systems (5G) candidate frequency. The specifications and performance of the exposure set-up necessary for experiment on human body were detailed. In order to confirm the performance of constructed set-up, several measurements using phantom and real human were performed. Our future works include more detailed biological study, such as estimation on blood flow, electrocardiograph, and so on.

Acknowledgment

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References

[1] ICNIRP Guidelines, “Guidelines for limiting exposure to time-varying el ectric, magnetic, and electromagnetic fields (up to 300 GHz),” Health Ph ys., vol.74, no.4, pp.494–522, 1998.

[2] ICNIRP International Commission on Non-Ionizing Radiation Protectio n guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz) Health Phys. 99 818–36, 2010.

[3] IEEE Standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz, Std C95.1, 2005.

[4] “Measurement of SAR from Mobile Phone Terminals and Other Termi nals that are Intended for Use in Close Proximity to the Side of the Hea d,” Telecommunications Technology Council Report, Deliberation no.11 8, 2000.

[5] L. Kun, K. Sasaki, S. Watanabe and H. Shirai, “Relationship between po wer density and surface temperature elevation for human skin exposure t o electromagnetic waves with oblique incidence angle from 6 GHz to 1 THz,” Physics in medicine and biology, vol.64, no.6, 2019.

[6] K. Sasaki et al., “Dosimetry Using a Localized Exposure System in the Millimeter-Wave Band for in vivo Studies on Ocular Effects”, IEEE Tra ns. Microw. Theory Tech., vol.62, no.10, pp.3311-3318, 2015.

[7] T. Shiina, Y. Suzuki, K. Sasaki, S. Watanabe and M. Taki, “High efficie ncy applicator based on printed circuit board in millimeter-wave region,” IEEE Trans. Microw. Theory Tech., vol.63, no.10, pp.3311-3318, Oct. 2015.

[8] S. N. Enomoto et al., “O2 Thermal sensation threshold (TST) when expo sed to millimeter waves (MMWS) in japanese,” Clinical Neurophysiolog y, vol.128. no.9, e180, 2017.

[9] D. Funahashi, A. Hirata, S. Kodera and K. R. Foster, “Area-Averaged Tr ansmitted Power Density at Skin Surface as Metric to Estimate Surface Temperature Elevation,” IEEE Access, vol.6, pp.77665-77674, 2018.

[10] Y. Hashimoto, A. Hirata, R. Morimoto, S. Aonuma, I. Laakso, K. Jokela and K. R. Foster,”On the averaging area for incident power density for h uman exposure limits at frequencies over 6 GHz,” Physics in Medicine a nd Biology, vol.62, no.8, pp.3124-3138, 2017.

[11] K. Sakakibara, T. Sekiguchi and T. Hikage: "Development of 28 GHz ba nd exposure equipment for studies on thermal perception thresholds of b iological effects exposed to millimeter-wave at 5th generation wireless s ystems candidate frequency band,” proc. of BioEM 2018, PB-58, pp.646 -648, Jun. 2018.

[12] Schmid & Partner Engineering AG, SEMCAD X, https://www.semcad.c om/.

[13] C. Gabriel, S. Gabriel and E. Corthout, "The dielectric properties of biol ogical tissues: I. Literature survey," Physics in medicine and biology, vol. 41, no.11, pp.2231-2249, 1996.