Investigating Thermal Cooling Mechanisms of Human Body Under Exposure to Electromagnetic Radiation

HUAN HUAN ZHANG[1], (Member, IEEE), **YING LIU**[1], (Senior Member, IEEE), **XIAOYAN Y. Z. XIONG**[2], (Member, IEEE), **GUANG MING SHI**[3], (Senior Member, IEEE), **CHUN YANG WANG**[4], AND **WEI E. I. SHA**[5], (Senior Member, IEEE)

[1]National Key Laboratory of Antennas and Microwave Technology, School of Electronic Engineering, Xidian University, Xi'an 710071, China
[2]ZJUI Institute, International Campus, Zhejiang University, Haining 314400, China
[3]School of Artificial Intelligence, Xidian University, Xi'an 710071, China
[4]College of Clinical Medicine, Xi'an Medical University, Xi'an 710021, China
[5]College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310058, China

Corresponding author: Ying Liu (liuying@mail.xidian.edu.cn)

ABSTRACT Thermal cooling mechanisms of human exposed to electromagnetic (EM) radiation are studied in detail. The EM and thermal co-simulation method is utilized to calculate the and temperature distributions. Moreover, Pennes' bioheat equation is solved to understand different thermal cooling mechanisms, including blood flow, convective cooling, and radiative cooling separately or jointly. The numerical results demonstrate the characteristics and functions for each cooling mechanism. Different from the traditional view that the cooling effect of blood is usually reflected by its influence on sweat secretion and evaporation, this paper indicates that the blood flow itself is an important factor of thermal cooling, especially for high-intensity EM radiation. This paper contributes to the fundamental understanding of thermal cooling mechanisms of human.

INDEX TERMS Cooling mechanism, EM radiation, human, finite-element method.

I. INTRODUCTION

Humans and other endotherms have thermoregulation mechanisms to maintain their body temperature at a stable level even when their ambient temperature changes. The temperature of human body is physiologically divided into shell temperature and core temperature. Human beings have a core temperature of around 37°C, at which the human body systems operate in optimum [1]–[5]. With the extensive use of electromagnetic (EM) field and microwave technology, EM radiation becomes pervasive in people's daily life. The EM radiation can originate from household electrical appliance, mobile phones, mobile communication base station, medical equipment, high voltage electric power equipment, radar, laser, etc. The most immediate hazard of EM radiation is the increment of temperature of tissues and organs. If the body temperature deviates too much from the core temperature, it will have an adverse impact on organism. For instance,

it is reported that high temperature will increase the blood-brain-barrier permeability, making it easier for the neurotoxic metabolites produced by peripheral organs and tissues to enter the brain. Thus the brain cells will be damaged when the temperature is above 40°C [6]. When the temperature is above 42°C, a series of cytotoxic events will occur, such as protein denaturation, aberrant oxidative phosphorylation and impaired DNA synthesis, resulting in multiorgan failure and neuron non-reversible damage [7]. In severe cases, people may exhibit symptoms of hypotension, shock, heart failure, hydrocephalus and even death [8]–[10]. Therefore a thorough study of the thermal cooling mechanisms of human under exposure to EM radiation is both necessary and significant, which will establish a theoretical foundation for the prevention and therapy of thermal damage of human body.

In existing textbooks of medical physiology, the thermal cooling mechanisms of human body mainly include

conduction, convection, radiation and evaporation [1], [2]. The heat in the internal of human body is transferred to the skin by thermal conduction. The skin can also conduct heat to whatever it is in direct contact with. Convection cooling occurs when the skin is surrounded by cool air. The air nearby the skin is warmed by the skin and its density decreases. As a result, the warmed air goes upward. Then the cool air in the vicinity will fill the vacancy and be warmed again. In such a manner, the heat of human body is transferred to the air. All objects that have a temperature higher than absolute zero radiate electromagnetic waves to surroundings. The temperature of human body is obviously higher than absolute zero. To transfer heat, human emits electromagnetic waves to surroundings through its skin. When the skin of human sweats out moisture, the evaporation of the liquid promotes heat loss [11].
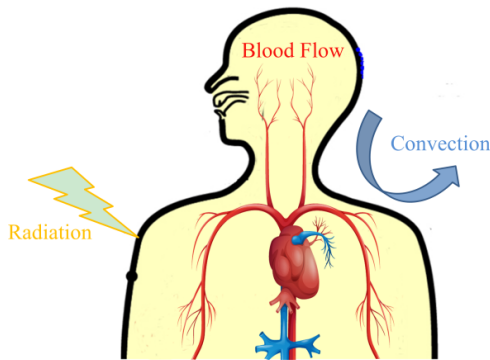

FIGURE 1. Cooling mechanisms of human body.

Experimental study of the thermal cooling mechanisms on a living person is inconvenient for two reasons. It is difficult to conduct single factor analysis because the cooling mechanisms of human usually work in concert. Moreover, it is unethical to let a person stay under strong EM radiation or high ambient temperature. Consequently, in this work, a three-step electromagnetic and thermal co-simulation method [12]–[21] is adopted to study the thermal cooling mechanisms of human under exposure to EM radiation. Firstly, the finite element-iterative integral equation evaluation (FE-IIEE) method is utilized to solve the Helmholtz vector equation for the analysis of the electric field distribution inside a human head model beside an antenna [22], [23]. Secondly, the rate of electromagnetic energy absorbed by the biological tissues is represented by the specific absorption rate (SAR) value. At last, thermal simulation is performed to obtain the temperature distribution by solving the Pennes' bioheat equation with the time-domain finite element method (TDFEM) [24], [25]. The thermal cooling mechanisms of human is discussed in detail. A thorough study of the contributions of blood flow, convection and radiation for thermal cooling is carried out as shown in Fig. 1. Different from the traditional view that the cooling effect of blood is usually reflected by its influence on sweat secretion and evaporation,

our study indicates that the blood flow itself is an important factor of thermal cooling.

II. METHODS
Firstly, the Helmholtz vector equation is solved to obtain the electric field distribution inside a human head model [22]:

$$\nabla \times \left(\mu_r^{-1} \nabla \times \mathbf{E} \right) - k_0^2 \varepsilon_r \mathbf{E} = 0, \tag{1}$$

where $\mathbf{E}$ represents the electric field. μ_r refers to the relative permeability. ε_r denotes the relative permittivity. k_0 is the wave number in free space.

Secondly, the SAR values are calculated to represent the rate of electromagnetic energy absorbed by the biological tissues:

$$SAR = \frac{\sigma \, |\mathbf{E}\,(\mathbf{r})|^2}{\rho}, \tag{2}$$

where σ is the conductivity, and ρ represents the density.

Thirdly, in order to understand the thermal cooling mechanisms of human, Pennes' bioheat equation is adopted for the thermal simulation [26]:

$$\rho c_\rho \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T) + \rho SAR + Q_m - B\,(T - T_{blood}), \tag{3}$$

where T is the unknown temperature of a tissue as a function of time and space. c_ρ refers to the specific heat capacity. κ is the thermal conductivity. Q_m denotes the metabolic heat generation. T_{blood} is the blood temperature, and it is always close to the core temperature of human. B is related to the blood perfusion.

A detailed description of the above three-step electromagnetic and thermal co-simulation method can be found in [12]. Actually, equation (3) is a revised version of traditional heat conduction equation by replacing the heat source with metabolic heat source and electromagnetic heat source [27], [28]. Meanwhile, the last term $-B\,(T - T_{blood})$ related to the blood flow is added to represent the heat exchange between the human tissues and blood. It can be observed that when the temperature of a tissue is higher than that of the blood, the last term is negative and the blood serves as a heat sink. The heat will be transferred from tissues to blood. Otherwise, the blood is a heat source. The heat will be transferred from blood to tissues. Thus the blood flow has very special thermal effects on the local tissue temperature.

Mathematically the differential equation (3) has unique solution only if its boundary conditions are given. The boundary of human body is the skin. Physically, heat transfer occurs between the skin and its surroundings through convection, radiation and evaporation. Due to the limitation of the Pennes' bioheat equation, evaporation is not considered in this work. The convection boundary condition and radiation boundary condition are adopted on the skin-air interface to describe the convection and radiation cooling mechanisms.

The convection boundary condition is expressed as

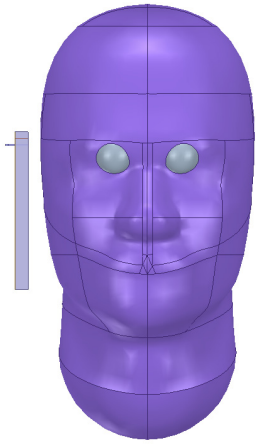$$-\hat{n} \cdot \kappa \nabla T = h\,(T - T_{amb}), \tag{4}$$

FIGURE 2. A human head model beside an antenna.

where h represents the convective heat transfer coefficient, T_{amb} denotes the ambient temperature. $\hat{n}$ denotes the unit outward normal vector of the boundary surface.

The radiation boundary condition is given by

$$-\hat{n} \cdot \kappa \nabla T = \varepsilon_0 \sigma \left(T^4 - T_{amb}^4 \right), \qquad (5)$$

where ε_0 refers to the emissivity of the skin, $\sigma = 5.68 \times 10^{-8} W/m^2 K^4$ is the Stefan-Boltzmann constant.

Solving the Pennes' bioheat equation with the specific boundary conditions, 1) we can study the thermal cooling

TABLE 1. Electromagnetic and thermal parameters of head model.

Tissues	ε_r	σ	κ	c_ρ	ρ	Q_m	B
Skin	41.4	0.87	0.42	3500	1010	1000	9100
Fat	11.3	0.11	0.25	2500	920	180	520
Muscle	55.0	0.94	0.5	3600	1040	690	2700
Bone	12.5	0.14	0.4	1300	1810	0	1000
CSF	74.0	2.12	0.6	4000	1010	0	0
Brain	45.8	0.77	0.5	3630	1040	10000	35000
Eye	49.6	0.994	0.53	3615	1052	0	0

of human body with or without external EM heat source at different ambient temperature. 2) we can capture the heat conduction from the internal of human body to the skin. 3) We can investigate the contributions of different cooling mechanisms involving convection, radiation and blood flow separately or jointly.

III. NUMERICAL EXPERIMENTS and DISCUSSIONS

A human head model is exposed to the EM radiation of an antenna as shown in Fig. 2. The head model consists of skin, fat, muscle, cortical bones, cerebrospinal fluid (CSF), brain and eyes. The corresponding electromagnetic and thermal parameters of the tissues are given in Table 1. The antenna is put beside the head model with a gap distance of 1 cm. Its working frequency is 900 MHz.
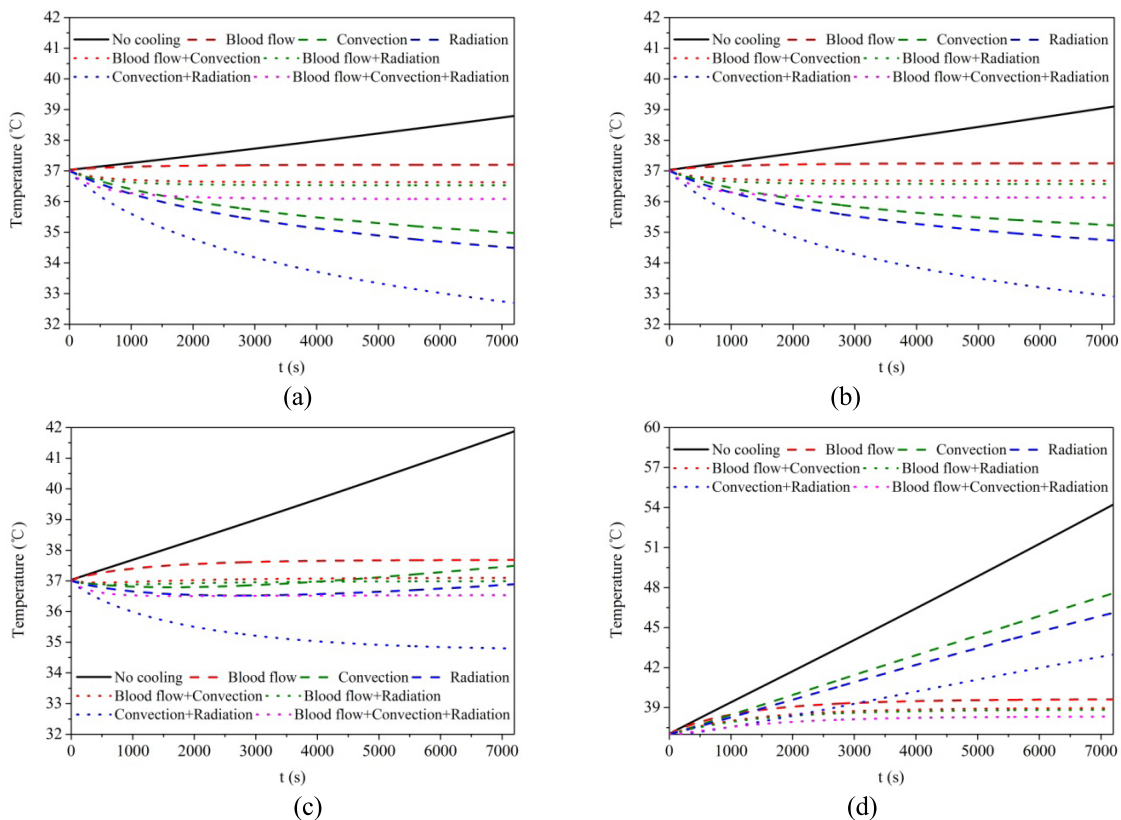

(a)

(b)

(c)

(d)

FIGURE 3. Real-time average body temperatures at ambient temperature=25°C, the input power of the antenna equals (a) 0 W (b) 1 W (c) 10 W (d) 50 W.
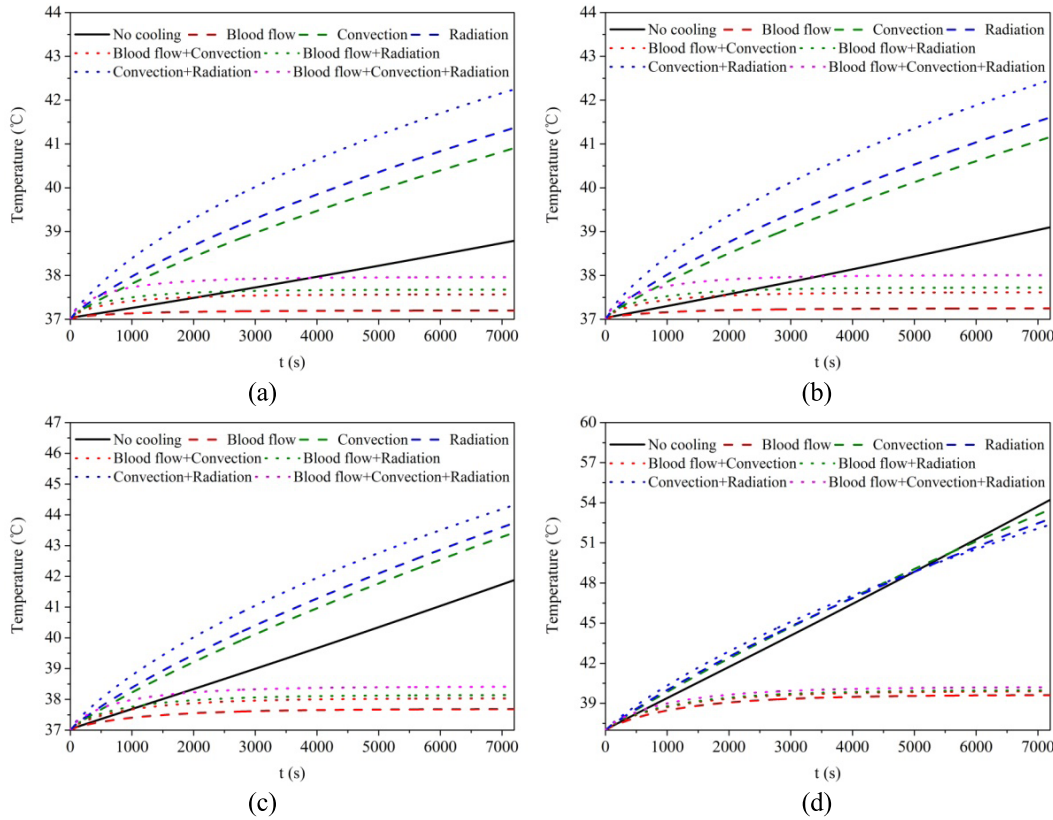
FIGURE 4. Real-time average body temperatures at ambient temperature=45°C, the input power of the antenna equals (a) 0 W (b) 1 W (c) 10 W (d) 50 W.

The following assumptions are made before the cooling mechanisms of human are investigated:

1) The experimental subject is a normotensive male, who is awake at complete rest with no muscle activity and in a non-stressed state. Under such a condition, the metabolic rate Q_m and the blood flow related term B are given in Table 1 [13].

2) The EM radiation to the experimental subject is local. Thus the blood temperature can be the same as the core temperature due to blood circulation for a limited period.

3) The electromagnetic and thermal properties of human tissues are constant in our experiment.

4) The ambient temperature is homogeneous.

5) Free convection occurs between the skin and the air if convection cooling exists, $h = 5W/(m^2 \cdot K)$ [29].

6) The emissivity of the skin of the experimental subject is $\varepsilon_0 = 0.95$ [29].

In the numerical experiment, $T_{amb} = 25°C$ and $T_{amb} = 45°C$ are considered corresponding to two situations that the ambient temperature is lower or higher than the body temperature of human. The input power of the antenna is set to be 0 W, 1 W, 10 W and 50 W to model different EM radiation sources. At a fixed ambient temperature and input power of the antenna, the average body temperatures are calculated by considering different thermal cooling mechanisms including convection, radiation, blood flow, and their combinations. The obtained real-time average body temperatures are shown in Fig. 3 and Fig. 4.

In Fig. 3 and 4, "No cooling" means that the skin surface is adiabatic. Convection cooling and radiation cooling do not exist. Meanwhile, there is also no blood flow in this case. Moreover, "Blood flow", "Convection" and "Radiation" suggest that there exists only one cooling mechanism. Furthermore, "Blood flow + Convection", "Blood flow + Radiation" and "Convection + Radiation" refer to that two of the three cooling mechanisms co-work. Additionally, "Blood flow + Convection + Radiation" corresponds to that all of the three cooling mechanisms take effect.

A. NO COOLING

Look at the black line in Fig. 3 and 4, the body temperature keeps rising due to the metabolic heat source and the EM radiation of antenna. Since the skin is adiabatic with the environment, the ambient temperature has no influence on the body temperature. So the results corresponding to "no cooling" in Fig. 3 and Fig. 4 are the same. At a fixed ambient temperature, the temperature rises faster when the input power of the antenna is larger.

B. ONLY CONVECTION OR RADIATION

According to Fig. 3 (a)-(d), when only convection or radiation is considered, the body temperature decreases compared with the case of "no cooling" at ambient temperature of 25°C. Moreover, radiative cooling is more effective than

convective cooling. According to Fig. 4 (a)-(c), both the convective cooling and radiative cooling lose efficacy at ambient temperature of 45°C because the ambient temperature is higher than the body temperature. Heat will be transferred from the surroundings to human body through convection and radiation. The result of Fig. 4 (d) is interesting. There is an intersection point between the black line and the blue dashed line or between the black line and the green dashed line. Before the intersection point, the body temperature increases compared to the case of "no cooling" since the environment temperature is higher than the body temperature. After the intersection point, the body temperature is higher than the environment temperature. As a result, convective cooling and radiative cooling take effect. The body temperature becomes lower than that of "no cooling".

C. ONLY BLOOD FLOW

Use the case of "no cooling" as a baseline, when the body temperature is slightly higher than the core temperature as shown in Fig.3 (a)-(c), the cooling effect of blood flow is weaker than convection and radiation. However, when the input power of the antenna is large as shown in Fig. 3 (d), the body temperature is much higher than the core temperature. The cooling effect of blood flow becomes more remarkable than either of convection and radiation. This phenomenon is especially apparent when convective cooling and radiative cooling lose efficacy at ambient temperature of 45°C in Fig. 4. Moreover, it can be observed that the blood flow does not continuously decrease the body temperature. It can make the body temperature stable around the normal core temperature of 37°C.

D. COMBINATION OF COOLING MECHANISMS

The case of "Convection + radiation" is similar with the case of only convection or radiation. Moreover, "Convection + radiation" decreases or increases the body temperature faster than only convection or radiation at the ambient temperature of 25°C or 45°C.

The cases of "Blood flow + Convection", "Blood flow + Radiation" and "Blood flow + Convection + Radiation" are very similar. Take the case of "Blood flow + Convection" as an example and compare it to the case of "Convection". As shown in Fig.3 (a) and Fig.3 (b), "Convection" decreases the body temperature below 37°C. While with the consideration of blood flow, "Blood flow + Convection" can increase the body temperature above 37°C. In Fig. 3(c), there is an intersection point between the green dashed line and the red dotted line. Before the intersection point, the body temperature is decreased below 37°C with "Convection", while it will be increased around 37 °C with "Blood flow + Convection". After the intersection point, "Convection" cannot offset the temperature increase induced by EM radiation and metabolic heat. The body temperature becomes higher than the core temperature. The blood flow starts to decrease the body temperature. So the body temperature of "Blood
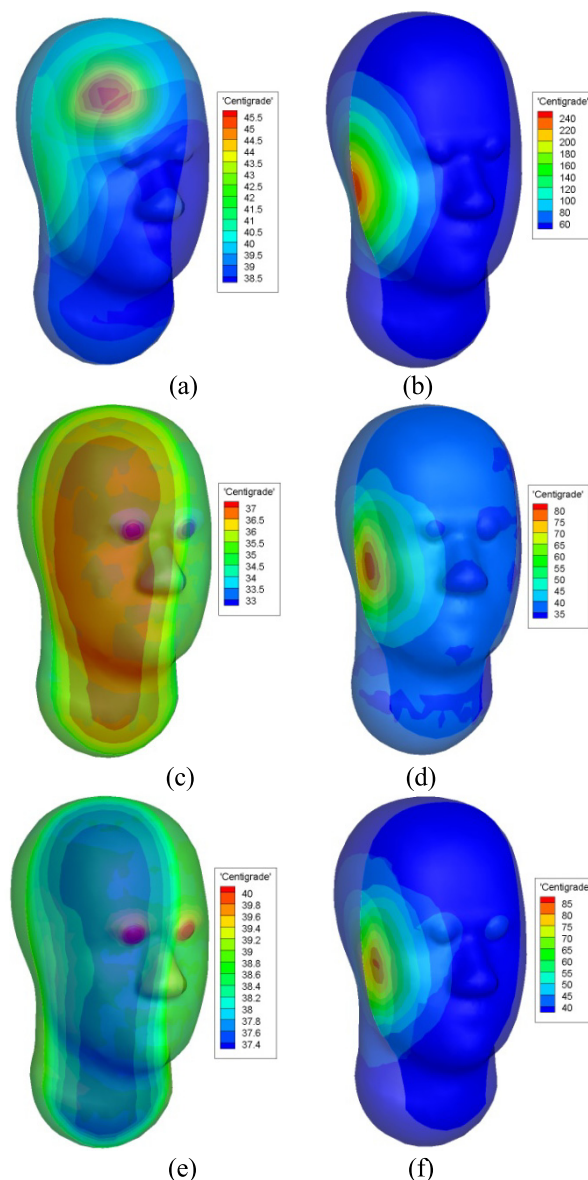

FIGURE 5. 3-D temperature distributions of human head model (a) Input power of 1 W, no cooling; (b) Input power of 50 W, no cooling; (c) Input power of 1 W, ambient temperature of 25°C, blood flow-convection-radiation combination; (d) Input power 50 W, ambient temperature of 25°C, blood flow-convection-radiation combination; (e) Input power of 1 W, ambient temperature of 45°C, blood flow-convection-radiation combination; (f) Input power of 50 W, ambient temperature of 45°C, blood flow-convection-radiation combination.

flow + Convection" is lower than "Convection" after the intersection point. In Fig.3 (d) and Fig.4 (a)-(d), "Convection" cannot effectively decrease the body temperature or will increase it. But after adding the contribution of blood flow, the cooling effect is very evident. Especially when the ambient temperature is 45 °C and the input power of the antenna is high, "Blood flow+ Convection" can guarantee the body temperature not far from the core temperature. Based on the above observation, the blood will heat the body when the body temperature is lower than the core temperature, while it

will cool the body when the body temperature is higher than the core temperature.

Figure 5 demonstrates the 3D temperature distributions at t=7200 s corresponding to "no cooling" or "Blood flow + Convection + Radiation" under the input power of antenna 1 W and 50 W at ambient temperature 25°C and 45°C. It can be observed that the body temperature will be increased drastically due to high-power EM radiation if there is no cooling. If the power of the EM radiation is low, the temperature distribution is relatively uniform and the hotspot will be in the center of the head model. If the power of the EM radiation is high, the hotspot will approach the source of radiation. With the consideration of the all-combined cooling mechanisms, the body temperature can be decreased effectively. On one hand, under high EM radiation (50 W), the temperature of hotspots close to the EM source is still much higher than the core temperature. On the other hand, under low EM radiation (1 W), the Human's eyes are the most dangerous places above the core temperature.

IV. CONCLUSION

In this paper, electromagnetic and thermal co-simulation is carried out to analyze the cooling mechanism of human under exposure to EM radiation. Different thermal cooling mechanisms include blood flow, convective cooling, radiative cooling and their combinations are investigated at different ambient temperature. Numerical experiments show that convective cooling and radiative cooling rely heavily on the temperature difference between the body temperature and the ambient temperature. They are effective only when the ambient temperature is lower than the body temperature. Moreover, radiative cooling is more effective than convective cooling. Most importantly, the blood flow is very important for the thermoregulation of human body. It can increase the body temperature when the body temperature is lower than the core temperature and decrease the body temperature when the body temperature is higher than the core temperature. Especially when the body temperature is lower than the ambient temperature, the blood flow becomes the most effective cooling mechanism in human body.

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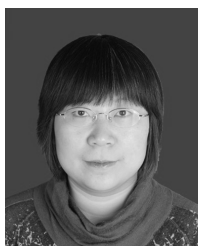
HUAN HUAN ZHANG (M'16) received the Ph.D. degree in electromagnetic field and microwave technology from the Nanjing University of Science and Technology, in 2015. He was a Post-Doctoral Research Fellow with the Center of Electromagnetics and Optics, The University of Hong Kong, Hong Kong, from 2015 to 2016. He is currently a Lecturer with the School of Electronic Engineering, Xidian University, Xi'an, China. His current research interests include multiphysics simulation, bioelectromagnetics, and computational electromagnetics.

Dr. Zhang serves as a Reviewer for the IEEE TRANSACTIONS ON ANTENNA AND PROPAGATION, the IEEE ACCESS, *Communications In Computational Physics*, the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, the IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, *IET Radar, Sonar and Navigation*, and *Applied Computational Electromagnetic Society Journal*.

YING LIU (SM'17) received the B.Eng., M.S., and Ph.D. degrees in electromagnetics from Xidian University, Xi'an, Shaanxi, China, in 1998, 2001, and 2004, respectively. From 2006 to 2007, she was a Post-Doctoral Researcher with Hanyang University, Seoul, South Korea. She is currently a Full Professor and the Director of the National Key Laboratory of Science and Technology on Antennas and Microwaves, Xidian University. She has authored or co-authored over 100 refereed journal papers, including *Prediction and Reduction of Antenna Radar Cross Section* (Xi'an: Xidian University Press, 2010) and *Antennas for Mobile Communication Systems* (Beijing: Electronics Industry Press, 2011). Her current research interests include antenna theory and technology and prediction and control of antenna radar cross section.

Dr. Liu is a Senior Member of the Chinese Institute of Electronics and a Fellow of IET. She was a recipient of the New Century Excellent Talents in the University of the Ministry of Education for China, in 2011. She is a Reviewer for several international journals. She serves as a TPC Member or a Session Chair for several IEEE flagship conferences. She also serves as an Associate Editor for the IEEE ACCESS.

XIAOYAN Y. Z. XIONG (M'12) received the B.S. degree from Southwest Jiaotong University, Chengdu, China, in 2008, the M.S. degree from Peking University, Beijing, China, in 2011, and the Ph.D. degree from The University of Hong Kong, Hong Kong, in 2015. She is currently an Assistant Professor with the ZJU-UIUC Institute, International Campus, Zhejiang University, Haining, China. Her current research interests include nonlinear optics, computational and applied electromagneticcs, and nano optics.

GUANG MING SHI (SM'10) received the B.S. degree in automatic control, the M.S. degree in computer control, and the Ph.D. degree in electronic information technology from Xidian University, in 1985, 1988, and 2002, respectively. In 1988, he joined the School of Electronic Engineering, Xidian University, where he has been a Professor, since 2003. From 1994 to 1996, he was a Research Assistant with the Department of Electronic Engineering, The University of Hong Kong. In 2004, he was the Head of the National Instruction Base of Electrician and Electronic. In 2004, he had studied at the Department of Electronic Engineering, University of Illinois at Urbana–Champaign. He is currently the Vice President of Xidian University. He has authored or co-authored over 60 research papers. His current research interests include compressed sensing, theory and design of multirate filter banks, image denoising, low bit-rate image/video coding, and implementation of algorithms for intelligent signal processing (using DSP and FPGA).

CHUN YANG WANG received the Ph.D. degree in clinical medicine from Nanjing University, in 2016. She is currently a Lecturer with the College of Clinical Medicine, Xi'an Medical University, Xi'an, China. Her current research interests include virus infection and innate immunity and screening of antiviral drugs.

Dr. Wang is appointed as the Board Member of the Paediatric Gastroenterology Hepatology and Nutrition Specialized Committee of the Shanxi International Medical Exchange Association.

WEI E. I. SHA (SM'17) received the B.S. and Ph.D. degrees in electronic engineering from Anhui University, Hefei, China, in 2003 and 2008, respectively. From 2008 to 2017, he was a Post-Doctoral Research Fellow and, then, a Research Assistant Professor with the Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong. In 2017, he joined the College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou, China, where he is currently a Tenure-Tracked Assistant Professor. From 2018 to 2019, he was a Marie Skłodowska-Curie Individual Fellow with University College London. He has authored or co-authored 102 refereed journal papers, 100 conference publications, four book chapters, and two books. His Google Scholar citations are 4030 with a h-index of 27. His current research interests include theoretical and computational research in electromagnetics and optics, focusing on the multiphysics and interdisciplinary research, and fundamental and applied aspects in plasmonics, photovoltaics, metasurfaces, quantum electrodynamics, and computational electromagnetics. He is a Senior Member of the IEEE and a member of OSA. He served as an Editorial Board Member of *Progress In Electromagnetics Research* and as a Guest Editor for the IEEE JOURNAL ON MULTISCALE AND MULTIPHYSICS COMPUTATIONAL TECHNIQUES and *Applied Computational Electromagnetics Society Journal*. He received the Second Prize of Science and Technology from the Anhui Province Government, China, in 2015, the Thousand Talents Program for Distinguished Young Scholars of China, in 2007, and four best student paper prizes and one Young Scientist Award along with his students.

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