The Potential of Terahertz Technology to Revolutionize Cardiac Healthcare

Samar Elmaadawy, Isaac Chan, and Josep M. Jornet

Department of Electrical and Computer Engineering

Northeastern University

Boston, Massachusetts, United States

Email: {elmaadawy.s, i.chan, j.jornet}@northeastern.edu

Abstract—Advancements in wireless communication and nanotechnology are enabling a new healthcare era by bringing nanodevices that are worn and implanted in the human body into the realm of possibility for continuous health monitoring and early disease detection. Among human organs, the heart is especially complex and vulnerable to sudden, life-threatening events, therefore making continuous monitoring crucial. This paper investigates the feasibility of terahertz communication in real-time heart monitoring. A 2D COMSOL Multiphysics® model was developed to simulate the interaction between terahertz radiation and the heart. Our findings demonstrate that a terahertz wireless link between an implanted leadless pacemaker and an external device is technically feasible. While terahertz radiation has a higher thermal impact than optical frequencies, pulsed-time transmission can significantly reduce this effect. This study paves the way for a new era of non-invasive, continuous heart monitoring using terahertz technology.

Index Terms—COMSOL, Heart, Photothermal, Terahertz (THz), Biomonitoring.

I. INTRODUCTION

Advancements in nanotechnology have enabled the design and production of nanoscale devices, revolutionizing the healthcare field by paving the way for a new implantable device era. Among other uses, these nanoscale devices are expected to be used to monitor and track the activity of human organs for early disease detection and to manage treatment plans. For example, monitoring the human liver, kidneys and lungs can help detect exposure to harmful substances and prevent organ failure, while monitoring the brain can help detect early signs of neurological disorders and assess the risk of cognitive impairment. One particular organ, the human heart, is the cornerstone of life, pumping blood throughout the entire body. Monitoring the heart is therefore paramount for early disease detection, prevention of severe complications, and managing cardiovascular disease treatment plans. There are many aspects of the heart that require monitoring, including heart rate, heart rhythm, blood pressure and flow, and oxygen and electrolyte levels. Traditionally, electrocardiograms (EKG), Holter monitors, echocardiograms, cardiac computed tomography (CT) scans, cardiac magnetic resonance imaging (MRI), and sphygmomanometers are used to monitor heart functionality. However, these methods require time and frequent doctor visits, which can delay the detection of certain conditions. Therefore, wirelessly monitoring cardiac activity and health status through wearable and implantable devices is essential for providing continuous real-time data, offering efficient and effective health monitoring [1].

Progress in wireless communication protocols enables implantable devices to transmit signals to wearable and external monitoring systems. This eliminates the need for wires or cables and significantly reduces the risk of infections. For instance, researchers have been exploring replacing traditional pacemakers with leadless pacemakers because the attached leads can serve as a conduit for bacterial entry into the bloodstream [2]. Ideally, a leadless pacemaker is expected to be placed in the right ventricle of the heart, sense and restore a normal rhythm by stimulating the heart muscle, and wirelessly communicate with either another implant or a wearable device. Two prominent examples of leadless pacemaker systems that are being tested and improved are Abbott's Nanostim [3] and Medtronic's Micra [4]. One of the challenges is the device's battery lifetime; however, some research groups are designing implantable nanoscale devices that convert the mechanical motion of the heart into electric energy [5]. Another challenge is the transmission range and power consumption. A possible solution to these challenges lies in terahertz technology.

Recently, the sub-terahertz and terahertz frequency bands (0.1 THz – 10 THz) have attracted interest in the healthcare field due to their sensing, imaging, and communication capabilities. Terahertz technology offers wide bandwidth and minimal interference with existing wireless technologies. It also supports the design of compact nano- and microdevices, enabling on-body and in-body wireless networks [6]. It is expected to play a vital role in future generations of wireless technologies. However, more research is required to establish safety regulations for terahertz technologies before they can be widely adopted in real-life applications.

In this paper, we develop a COMSOL Multiphysics® model to investigate the feasibility of a leadless pacemaker operating at terahertz frequencies, considering the crucial role of blood in regulating the body temperature. We examine permissible operating power levels and account for variations in the thermal properties of heart tissue among individuals. We analyze the thermal effects of terahertz electromagnetic radiation on cardiac tissue and blood within the heart ventricle.

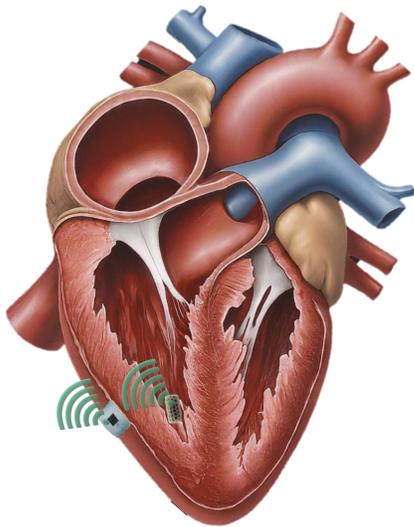Fig. 1. A 3D representation of the 2D model constructed on COMSOL Multiphysics®, which consisted of the heart and two implantable devices.

Additionally, we examine the impact of various pulse durations on cardiac tissue temperature. Finally, we compare the thermal effects of terahertz and optical frequencies in porcine heart tissue.

The remainder of the paper is organized as follows: Section II describes the developed photothermal model in COMSOL Multiphysics®, presenting the case studies and model parameters considered for each. Section III presents and discusses the obtained results, highlighting the permissible power limits for the defined system model and exploring various approaches to mitigate or reduce the thermal impact of terahertz radiation from wireless implants on the cardiovascular system. Finally, Section IV concludes the paper and outlines directions for future work.

II. MODEL FOUNDATIONS AND CASE STUDIES

In order to investigate the thermal impact of terahertz electromagnetic radiation from implantable nanodevices on the heart, we constructed a 2D model of the human heart on COMSOL Multiphysics®. The model is composed of the cardiac tissue and two blood chambers with a nanodevice in the right blood chamber and on the cardiac tissue from the outside, as in Fig. 1.

This model's physics is introduced and verified in [7]. A Gaussian beam with a $0.15\ mm$ beam width is used as a radiation source, and the Diffusion Approximation of the Radiative Transfer Equation is applied to model the power density changes in the exposed medium [8]. Following this step, the temperature increase in the exposed medium is estimated based on the radiation power density at each point on the medium and the absorption coefficient of that medium utilizing Pennes' Bioheat Equation [9]. This equation is widely used to predict temperature distribution in biological tissues due to its simplicity and computational efficiency. The model

accounts for accurate electrical and thermal parameters of the human cardiac tissue and blood based on what is found in the literature as presented in Table I. As demonstrated in [10], at terahertz frequencies, the scattering coefficient is negligible compared to the absorption coefficient, unlike at optical frequencies.

This research investigates the feasibility of terahertz wireless communication for human heart monitoring and its associated thermal effects. Specifically, we explored: (1) the ability of terahertz signals to penetrate the heart wall and be detected externally; (2) the thermal impact of terahertz radiation on cardiac tissue and blood; (3) the influence of pulse duration on tissue temperature changes; (4) the effects of variations in tissue thermal properties on temperature; and (5) the penetration depth of terahertz radiation in cardiac tissue and blood. All the mentioned simulations were conducted using human heart and blood properties. Finally, we compared the photothermal effects of terahertz radiation (1 THz) to optical frequencies (428.27 THz) using porcine tissue properties, as detailed human cardiac tissue data was limited in the optical frequencies range.

III. RESULTS AND DISCUSSION

A. Power Range for Safe Implant-to-Implant Communication

A leadless pacemaker, a small, battery-powered device implanted directly into the heart, requires wireless communication with external systems for monitoring and programming. To achieve this, an implantable device is placed on the heart wall as presented in Fig. 1. A key challenge is ensuring reliable communication while minimizing power consumption to prolong battery life and reduce the risk of tissue heating. Fig. 2 illustrates the relationship between the received power at the implantable device on the heart wall and the transmitted power density from the leadless pacemaker placed inside the right heart ventricle. Assuming a minimum receiver sensitivity of -155 dBm (equivalent to $3.16 * 10^{-16}\ mW$), which is more sensitive than typical Global Navigation Satellite System GNSS (-165 dBm), Long Range (LoRa) (-130 dBm), or cellular communication (-120 dBm), a minimum power density of $3.16\ \mu W/mm^2$ is required from the pacemaker for detection by the implanted device for a 1 THz electromagnetic signal.

The lower limit of power density is determined by the receiver's sensitivity for detecting the signal. Conversely, the upper limit of power density is constrained by the thermal changes induced in the tissue by the radiation. Fig. 3 shows the maximum temperature change in the heart due to the transmission of a continuous 1 THz signal for 5 s. Assuming a maximum allowable temperature increase of $1\ K$ to prevent overheating the tissue and potential long-term effects [19], the pacemaker can safely operate at power densities of up to $6.8\ mW/mm^2$. These power density boundaries, between $3.16\ \mu W/mm^2$ and $6.8\ mW/mm^2$, ensure both signal reception by the external device and the prevention of tissue damage. The power value will differ based on the implant location, sensitivity, and design.

| Parameter	Human Tissue		References	Porcine Tissue				References
	Heart	Blood		Heart		Blood		
Frequency (THz)	1			1	428.27	1	428.27	
Absorption Coefficient (1/cm)	150	210	[11], [12]	150	0.85	210	1.3	[12]–[15]
Reduced Scattering Coefficient (1/cm)	0	0	-	0	8.5	0	14	[14], [15]
Refractive Index	2.1	1.97	[11], [12]	2.2	1.44	1.97	1.42	[12]–[15]
Specific Heat Capacity (J/(kg.K))	3720	4000		3506		3800		
Thermal Conductivity (W/(m.K))	0.535	0.52	[16], [17]	0.504		0.492		[18]
Density (kg/m^3)	1050	1060		1037		1060		
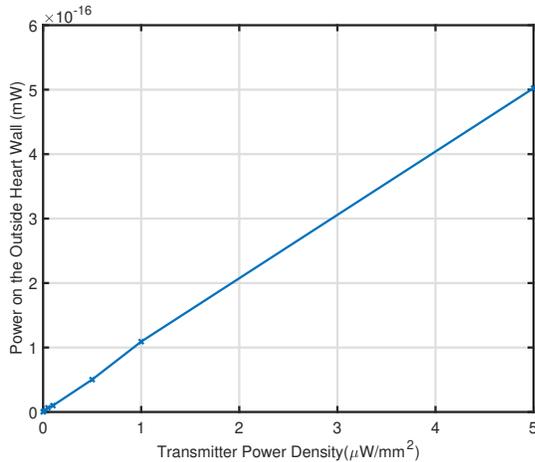
Fig. 2. The received power at the outside-the-heart implantable device vs. the transmitted power density from the inside-the-heart implantable leadless pacemaker.
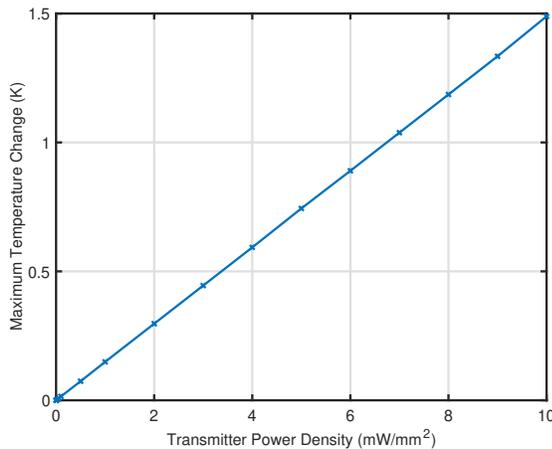

Fig. 3. The maximum temperature change in cardiac tissue due to the continuous propagation of a 1 THz signal for 5 s.
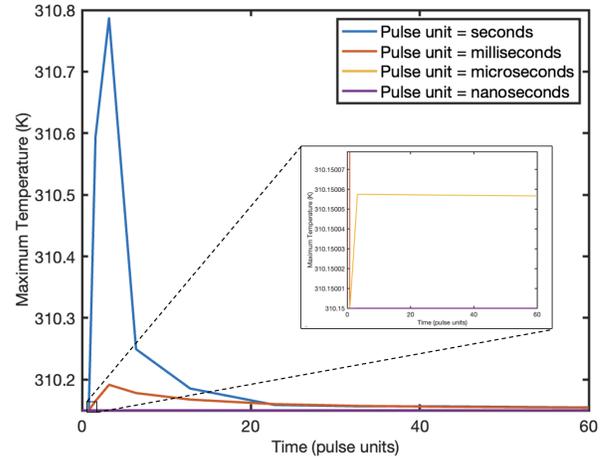

Fig. 4. The effect of different 1 THz pulsed radiation durations on the temperature changes of the heart at $5\ mW/mm^2$.

B. Thermal Effects due to Varied Pulsed-Signal Transmission

Continuous transmission from the implantable device is not necessary at all times, so sending pulses is a good strategy to save energy and limit exposure to electromagnetic radiation. Fig. 4 shows the temperature variation in the heart due to transmitting pulses with different durations. The longer the tissue is exposed to radiation, the higher its temperature becomes. For a 1 THz signal with a power density of $5\ mW/mm^2$, a 5-second pulse caused approximately a 0.65 K increase in temperature. However, a 5-millisecond pulse resulted in only a 0.05 K increase, while microsecond and nanosecond pulses had a negligible effect on the temperature.

The human body's blood plays a crucial role in regulating temperature. This is why, in all cases, there is a rise in temperature during transmission and a subsequent return to normal after the radiation stops. Interestingly, the rate of thermal dissipation is relatively slow, leading to a prolonged cooling period. For a 5 pulse unit duration, the cooling time is approximately 35 pulse units after transmission ceases. This information helps determine the optimal transmission frequency to prevent cumulative overheating.

As reported in the literature in [11], [12], the absorption coefficient of tissue increases with frequency. This directly correlates with a rise in tissue temperature, as illustrated in Fig. 5. For a given power level, a shorter pulse duration can
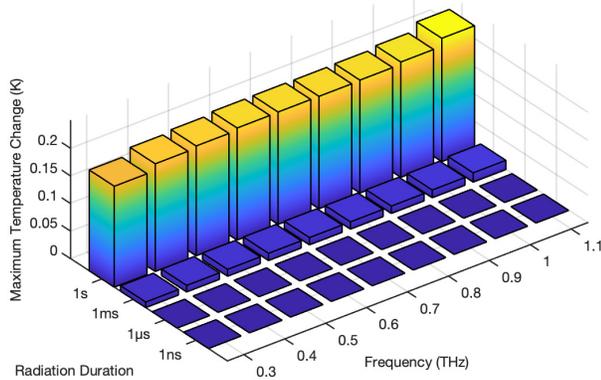
Fig. 5. The changes in maximum cardiac tissue temperature as pulse duration and frequency are changed, with power constant at 5 mW/mm^2.

Fig. 6. The changes in maximum cardiac tissue temperature after 5 ms of continuous radiation at 5 mW/mm^2 due to varying tissue thermal properties.

achieve the same temperature increase in the heart when using higher frequencies as a longer pulse of lower frequency. This highlights the importance of carefully controlling both pulse duration and frequency to mitigate health risks.

C. Thermal Effects due to Variations in Cardiac Thermal Properties

The thermal properties of the heart, including specific heat capacity, thermal conductivity, and tissue density, vary among individuals based on factors such as age, fitness, and gender. To ensure that the established safety limits are applicable to a wide range of individuals, it is essential to study the effects of different thermal property values.

For this study, the terahertz beam is applied to the heart wall. By changing one thermal property at a time while maintaining the others at average values, as found in literature in [20], we were able to assess the isolated impact of each parameter on cardiac tissue temperature. The results in Fig. 6 show that while there are variations in temperature due to different thermal property values, these variations are generally negligible at a power density of 5 mW/mm^2. However, at higher power levels, the variations might become more significant, although this is beyond the scope of the present study due to the established limit of 6.8 mW/mm^2 in Sec. III-A.

D. Penetration Depth in Cardiac Tissue vs. Blood

Cardiac tissue and blood exhibit distinct electrical and thermal properties, leading to differential interactions with terahertz electromagnetic radiation and consequently, varying temperature responses. While terahertz radiation is primarily absorbed within a shallow depth of a few hundred micrometers in biological tissues (around 0.2 mm in this case), Fig. 7 demonstrates that the resulting temperature changes can propagate significantly deeper, extending up to 0.8 mm into both the tissue and blood. This observation underscores the critical need
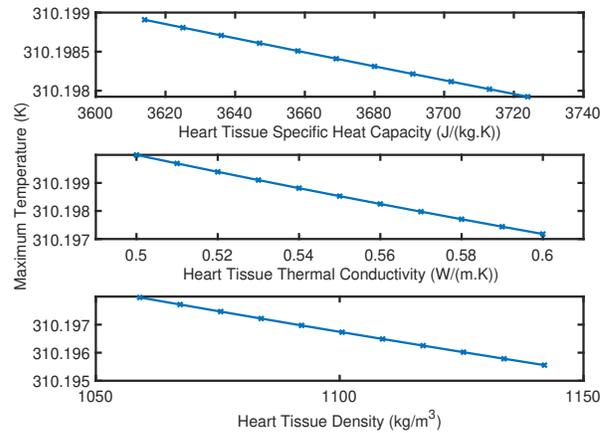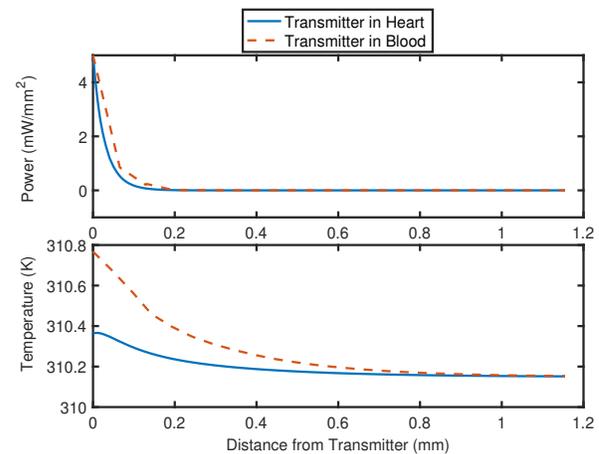

Fig. 7. The power and temperature penetrations from transmitters in the blood of the right ventricle and on the heart wall's tissue at 5 mW/mm^2.

for careful consideration of thermal effects in the design and implementation of next-generation cardiac device transmitters.

E. Temperature Changes at Terahertz vs. Optical Frequencies

Due to the limited availability of detailed optical property data for human cardiac tissue, this study utilized porcine heart and blood properties as a suitable surrogate. Fig. 8 presents the temperature changes within the heart tissue upon exposure to a 5 ms pulse of 1 THz and 428.27-THz radiation (corresponding to a wavelength of 700 nm) at a power density of 5 mW/mm^2. Absorption coefficients are typically higher at terahertz frequencies than at optical frequencies, leading to a greater temperature increase. However, this minor difference of 0.04 K, in this scenario, is considered negligible and can be further mitigated through the implementation of shorter pulse durations, lower terahertz frequencies, or reduced power levels. Consequently, despite the inherent thermal effects associ-
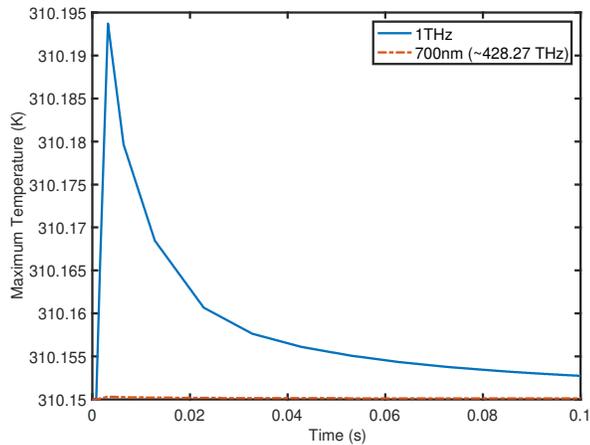
Fig. 8. Maximum temperatures for porcine heart at 1 THz and 428.27 THz (700 nm) frequencies and 5 mW/mm^2.

ated with the terahertz band, the potential for safe and effective terahertz-based cardiac applications remains promising.

IV. CONCLUSION

This study demonstrates the feasibility of establishing a terahertz wireless communication link from within the heart to an external receiver. Despite significant transmission losses, mainly because of absorption, the signal can be detected with a transmitter power density as low as 3.16 $\mu W/mm^2$. This power density is well below the threshold for causing noticeable temperature changes in the heart. Even at higher power densities up to 6.8 mW/mm^2, the temperature increase remains within acceptable limits of 1 K. However, by using shorter pulses instead of continuous transmission, the thermal impact can be further reduced. The optimal pulse duration may vary depending on the specific frequency used.

While individual cardiac tissue properties can differ based on factors like fitness, age, and gender, these variations have a minimal impact on the temperature changes within the discovered acceptable power density range. Our findings also highlight the higher photothermal effects of terahertz radiation compared to those of optical frequencies. Nonetheless, even at terahertz frequencies, the temperature increase remains manageable, suggesting that there is indeed potential for having safe and effective terahertz-based heart monitoring implantable devices.

Future research should focus on the design and development of practical terahertz-based implantable devices and systems for real-world applications in heart healthcare. By addressing challenges such as miniaturization, power efficiency, and biocompatibility, these devices could open the door to a new era of non-invasive, continuous heart monitoring.

REFERENCES

[1] T. F. Budinger, "Biomonitoring with wireless communications," *Annual Review of Biomedical Engineering*, vol. 5, no. 1, pp. 383–412, 2003.
[2] J. Z. Lee, S. K. Mulpuru, and W. K. Shen, "Leadless pacemaker: performance and complications," *Trends in Cardiovascular Medicine*, vol. 28, no. 2, pp. 130–141, 2018.
[3] R. S. Asirvatham, V. R. Vaidya, T. M. Thome, P. A. Friedman, and Y.-M. Cha, "Nanostim leadless pacemaker retrieval and simultaneous micra leadless pacemaker replacement: a single-center experience," *Journal of Interventional Cardiac Electrophysiology*, vol. 57, pp. 125–131, 2020.
[4] G. Z. Duray, P. Ritter, M. El-Chami, C. Narasimhan, R. Omar, J. M. Tolosana, S. Zhang, K. Soejima, C. Steinwender, L. Rapallini, *et al.*, "Long-term performance of a transcatheter pacing system: 12-month results from the micra transcatheter pacing study," *Heart rhythm*, vol. 14, no. 5, pp. 702–709, 2017.
[5] C. Dagdeviren, B. D. Yang, Y. Su, P. L. Tran, P. Joe, E. Anderson, J. Xia, V. Doraiswamy, B. Dehdashti, X. Feng, *et al.*, "Conformal piezoelectric energy harvesting and storage from motions of the heart, lung, and diaphragm," *Proceedings of the National Academy of Sciences*, vol. 111, no. 5, pp. 1927–1932, 2014.
[6] N. Saeed, M. H. Loukil, H. Sarieddeen, T. Y. Al-Naffouri, and M.-S. Alouini, "Body-centric terahertz networks: Prospects and challenges," *IEEE Transactions on Molecular, Biological, and Multi-Scale Communications*, vol. 8, no. 3, pp. 138–157, 2021.
[7] I. V. K. Reddy, S. Elmaadawy, E. P. Furlani, and J. M. Jornet, "Multiphysics analysis of electromagnetic wave propagation and photothermal heating in human tissues at terahertz and optical frequencies," *Scientific Reports*, 2023.
[8] F. Martelli, T. Binzoni, S. Del Bianco, A. Liemert, and A. Kienle, *Light propagation through biological tissue and other diffusive media: theory, solutions, and validations*. SPIE press Bellingham, Washington, 2022.
[9] H. H. Pennes, "Analysis of tissue and arterial blood temperatures in the resting human forearm," *Journal of applied physiology*, vol. 1, no. 2, pp. 93–122, 1948.
[10] H. Elayan, R. M. Shubair, J. M. Jornet, and P. Johari, "Terahertz channel model and link budget analysis for intrabody nanoscale communication," *IEEE transactions on nanobioscience*, vol. 16, no. 6, pp. 491–503, 2017.
[11] W. G. Yeo, *Terahertz spectroscopic characterization and imaging for biomedical applications*. The Ohio State University, 2015.
[12] C. B. Reid, G. Reese, A. P. Gibson, and V. P. Wallace, "Terahertz time-domain spectroscopy of human blood," *IEEE Transactions on Terahertz Science and Technology*, vol. 3, no. 4, pp. 363–367, 2013.
[13] G. J. Wilmink, B. L. Ibey, T. Tongue, B. Schulkin, N. Laman, X. G. Peralta, C. C. Roth, C. Z. Cerna, B. D. Rivest, J. E. Grundt, *et al.*, "Development of a compact terahertz time-domain spectrometer for the measurement of the optical properties of biological tissues," *Journal of biomedical optics*, vol. 16, no. 4, pp. 047006–047006, 2011.
[14] S. Mosca, P. Lanka, N. Stone, S. Konugolu Venkata Sekar, P. Matousek, G. Valentini, and A. Pifferi, "Optical characterization of porcine tissues from various organs in the 650–1100 nm range using time-domain diffuse spectroscopy," *Biomedical optics express*, vol. 11, no. 3, pp. 1697–1706, 2020.
[15] N. Bosschaart, G. J. Edelman, M. C. Aalders, T. G. van Leeuwen, and D. J. Faber, "A literature review and novel theoretical approach on the optical properties of whole blood," *Lasers in medical science*, vol. 29, pp. 453–479, 2014.
[16] F. A. Duck, "Thermal properties of tissue," in *Physical Properties of Tissues*, pp. 9–42, Elsevier, 1990.
[17] J. P. Rugh and D. Bharathan, "Predicting human thermal comfort in automobiles," *SAE transactions*, pp. 2508–2516, 2005.
[18] J. Urzova and M. Jelinek, "Heat transfer modelling of pulsed laser-tissue interaction," *Laser Physics*, vol. 28, no. 3, p. 036001, 2018.
[19] E. Fields, "Icnirp guidelines," *Health*, vol. 17, no. 9078/20, p. 0, 2020.
[20] P. A. Hasgall, F. Di Gennaro, C. Baumgartner, E. Neufeld, B. Lloyd, M.-C. Gosselin, D. Payne, A. Klingenböck, and N. Kuster, "IT'IS Database for thermal and electromagnetic parameters of biological tissues." Version 4.1, Feb. 2022. DOI: 10.13099/VIP21000-04-1, https://itis.swiss/database.