Study on Fat as the Propagation Medium in Optical-Based In-Body Communications

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Abstract. This paper investigates fat tissue as a medium for communication in implantable/ingestible medical device (IMD) systems based on optical wireless communication (OWC). The findings emphasize the importance of tissue characteristics (temperature in particular) for optimizing OWC performance. This study considered Near-infrared (NIR) light with 810 nm wavelength and fresh porcine samples to mimic the human tissue. The study employs a realistic measurement approach in an *ex vivo* setting using various porcine samples: pure fat and flesh tissues and samples with different thicknesses. This study also investigates the influence of porcine temperature on the optical communication channels, which are measured by comparing the received optical power at 23 °C and 37 °C. In general, tissue samples at warmer temperatures (37 °C) receive higher optical power than colder samples. The results also demonstrate the superior optical power transmission capabilities of pure fat compared to pure flesh in porcine tissue samples in warm conditions. We also found that porcine with multiple layers of fat (fatty sample) yields higher received optical power than porcine with multiple layers of flesh (muscular). The results of this study provide valuable insights and relevant considerations for OWC-based in-body communication conducted using porcine samples.

Keywords: Fat · Flesh · Porcine Sample · Optical Wireless Communication · Tissue Temperature · In-body Communications

1 Introduction

Medical in-body devices, or in the most literature called as implantable/ingestible medical devices (IMD), such as implants, smart pills, and biosensors, play an essential role in diagnosing, treating, and monitoring various clinical conditions of patients. The incorporation of wireless communication within these devices serves crucial functions, such as transmitting data, regulating device operations, and facilitating immediate communication with healthcare professionals [1]. Optical wireless communication (OWC) is

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emerging as a viable technology for in-body communication cases alongside established radio frequency (RF) and ultrasound technologies [2]. Numerous studies indicate that OWC offers advantages in the context of the in-body application, including its capacity to provide a substantial security level as the communication range is limited to a few millimeters [3], low power consumption [4, 5], electromagnetic interference-free operation, avoiding RF emission which might cause harm to tissues (if high transmission power or long exposure times are used) [6]. On the other hand, OWC has the ability to enable high-speed data transmission [7–9], making it an attractive option for the sixth generation (6G) of communication technology [10]. OWC also facilitates simultaneous energy and data transmission for IMD [11].

Having a thorough understanding of the optical channel's characteristics is essential to achieve a seamless design of in-body communication systems. It is widely acknowledged that signal propagation differs among various tissues, primarily due to variations in their optical properties [12]. In the context of the RF use case, research has shown that fat tissue offers the most advantageous conditions for signal propagation in terms of velocity and loss [12]. Significant studies have specifically explored the potential of fat tissue as a medium for medical applications; these cases were based on RF waves [13–16]; these seminal works have verified fat tissue's feasibility through simulation and measurement studies.

When brought to OWC, measurements conducted on anaesthetized animals yield the most realistic results as the optical properties of tissues begin to alter immediately after the animal's death. Nevertheless, conducting these measurements is challenging due to the need for a hospital environment with a strict clinical procedure. As an alternative, measurement using porcine samples are more practical to do. Porcine sample is frequently utilized in in-body communication studies, as it has similar optical properties to those of human beings [17]. There are specific considerations when using porcine samples: tissue temperature and tissue composition. The tissue temperature can affect its properties, thus influencing the characteristics of the optical channel within the body. The composition of fat and flesh layers in the porcine sample is believed to have a significant impact on the results, as fat is known to be a better conductive medium for signal transmission [17].

Despite the fat layer has been explored by various researchers on the RF domain, to the best of the authors' knowledge, no studies have been conducted that exploit optical channel characteristics, especially on porcine samples containing fat and flesh composition with realistic measurement. In addition, there is a lack of research examining the influence of porcine temperature on optical channel characteristics.

The objective of this study is to investigate the factors above: (*i*) The optical channel characteristics are assessed using porcine: pure fat and flesh tissue samples and samples with flesh and fat layers. (*ii*) The effect of the porcine sample's temperature on the received power. The specifications of the porcine samples were determined, and the measurements were conducted using two parameters: received power in milliwatts and power density in W/cm^2. These measurements were carried out using an 810 nm NIR LED, as NIR waves experience less attenuation compared to visible light wavelengths [18] and other wavelengths [19]. The optical power received in the OWC system is a crucial factor in determining its performance, as it is closely related to the signal-to-noise ratio (SNR) of the received signal [20–22]. Accordingly, before implementing an OWC system for in-body communication, understanding the tissue characteristics is one of the top priorities.

This paper is organized as follows: Section 2 presents brief description of OWC technology for in-body communication to bridge concepts for a wide audience, from the biomedical engineering, wireless communication, and healthcare technology standpoints. Section 3 described methodology followed in this study, including measurement tools and experiment procedures. Section 4 presents the Results and Analysis. Section 5 discusses the finding. Conclusions are given in Sect. 6.

2 OWC Technology for In-Body Communication

OWC is feasible approach to enable a wireless link through biological tissue as the receiver is able to receive optical power, offering highly secure communication to in-body devices that may be used in the future IMD such as modern pacemakers, defibrillators, insulin pumps, cochlear implants, brain implants, etc. [3].

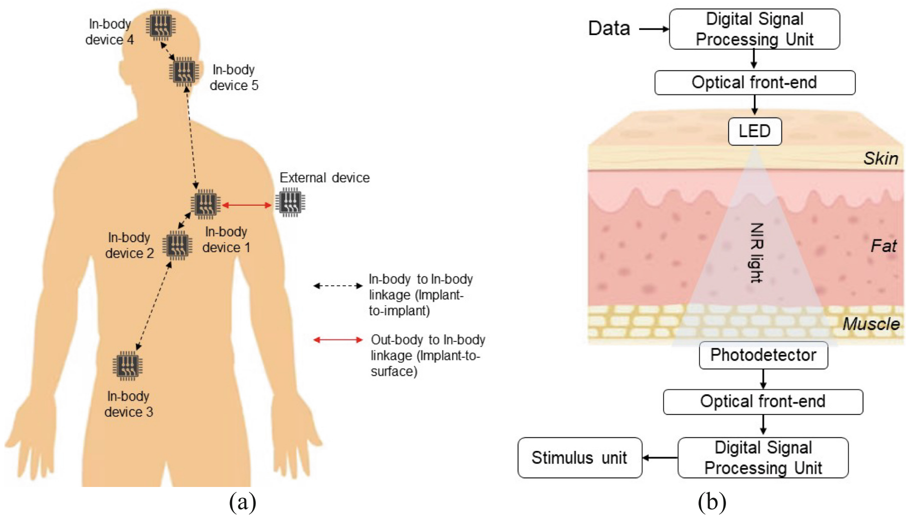


Fig. 1. OWC technology for in-body communication: (a) generic architecture; (b) used architecture

Communication modalities on in-body communication can be categorized into two distinct types: in-body to out-body linkage and in-body to in-body linkage communication (Fig. 1a). Surface-to-implant communication (out-body to in-body linkage) involves communication between in-body and external devices (out-body device) [23]. This type of communication is appropriate for situations where there is a need to transmit data collected from in-body devices to out-body devices for processing or to centralized control and diagnostics centers implant-to-implant communication (in-body to in-body linkage) refers to the communication between two in-body devices or more. This type of communication is commonly used in applications involving implants that operate in a closed-loop control system [24].

We will use the results of this study for the out-body to in-body communication, as a reference using OWC as a mechanism for providing information from outside to the human body. The system architecture for this purpose is illustrated in Fig. 2(b), which was adopted from [25, 26]. The system contains a digital processing unit transceiver, an optical front-end transceiver, a NIR LED as a transmitter, and a photodetector as a receiver device. The data comes from out-body device or host computer and is processed by a digital signal processing unit; the modulated data are emitted optically using the NIR LED. The data passed the biological tissue are captured by the photodetector and then is demodulated by the digital signal processing subsystem fed to the stimulus device. The implementation of this system is highly possible be applied to modern IMD, such as pacemakers, allowing for wireless control and monitoring through an OWC-based telemetry link.

3 Methodology

The measurements were conducted using commercially available equipment provided by *Thorlabs*. An experimental test-bed comprised an optical transmitter and an optical receiver (Fig. 2). The biological tissue was used as the optical medium. NIR light was chosen to illuminate the biological tissue as it has better propagation properties across tissues than other wavelengths [27], specifically between 800 nm and 900 nm [28]. The transmitter side implemented a driver (*Thorlabs* DC2200) and a mounted NIR LED (*Thorlabs* M810L3).

The LED driver module can be controlled easily using the front panel and a digital display, we used constant current mode in this study. The maximum current for the 810 nm LED was 500 mA, resulting in a maximum transmitted optical power of 372 mW and a maximum incident power density of 525 mW/cm^2, based on actual measurements using an optical sensor (*Thorlabs* S121C) connected to a power meter (*Thorlabs* PM100D). This power level was considered safe as it is below the maximum allowable limit (2 W/cm^2 in 1 sec using $\lambda = 830$ nm) according to the ANSI.Z136.1-2007 standard [29, 30]. The optical power meter was used to measure the received optical power. In this study, only two parameters were used: received power in milliwatts and power density in W/cm^2.

Pure fat and flesh tissues and thicker tissues were used for measurement. Each sample had dimensions of approximately 5 cm $\times$ 5 cm. The thickness of pure fat and flesh tissues are 1.5 cm. Three different thicknesses were used; it was composed of fat and flesh. Afterward, we labeled the thicker tissues as follow: sample #1 (30 mm), sample #2 (38 mm), and sample #3 (40 mm). All samples were freshly purchased from the local market at an initial temperature of 11 °C but were subsequently in a heat chamber to temperatures of 23 °C and 37 °C for measurement purposes.

The LED input current was varied (100 mA, 200 mA, 300 mA, 400 mA, and 500 mA) by controlling the driver module, and the corresponding optical power employed on the porcine sample was measured. The transmitted power of the LED varied depending on the electrical current, with values of 74.2 mW, 153 mW, 230 mW, 303 mW, and 372 mW observed for the given currents of 100 mA, 200 mA, 300 mA, 400 mA, and 500 mA, respectively.

The porcine sample's surface was illuminated by an NIR LED, while the optical sensor was positioned on the opposing side. The porcine sample heating was performed at different places to protect the test-bed from the heating process. In our measurement, once the sample has been heated and reached a temperature of 37 °C, it is promptly placed in a provided holder where the alignment of the NIR LED and sensor remains unchanged. This positioning remains consistent with previous measurements conducted at a temperature of 23 °C. The temperature of the porcine samples was kept below 44 °C to prevent excessive evaporation and potential harm caused by excessively high temperatures [31]. During the experiment, we strictly adhered to protective eyeglasses (certified laser safety glasses provided by Thorlabs) to minimize the potential risk of eye injuries from exposure to high radiation levels [32–34].

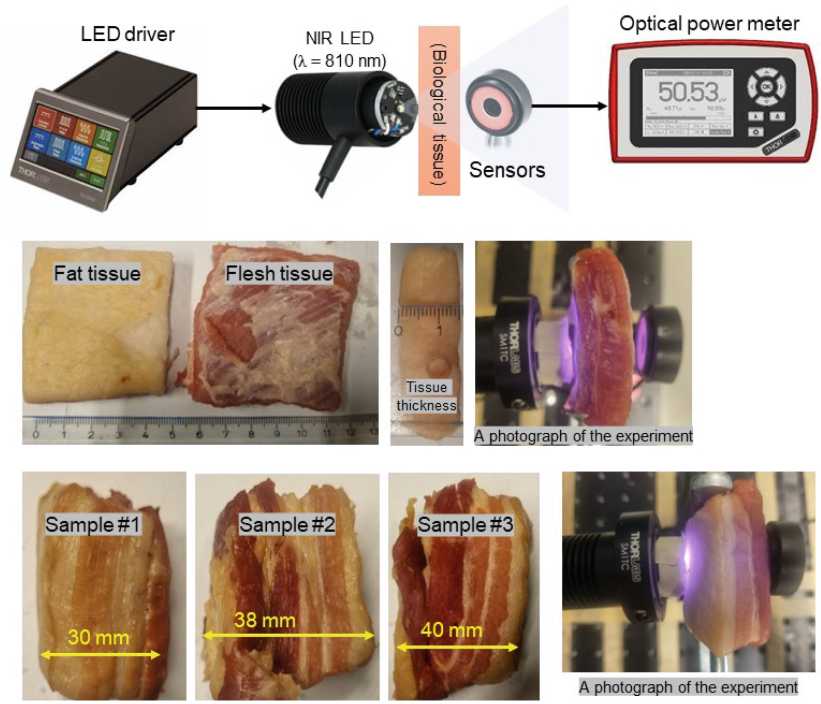
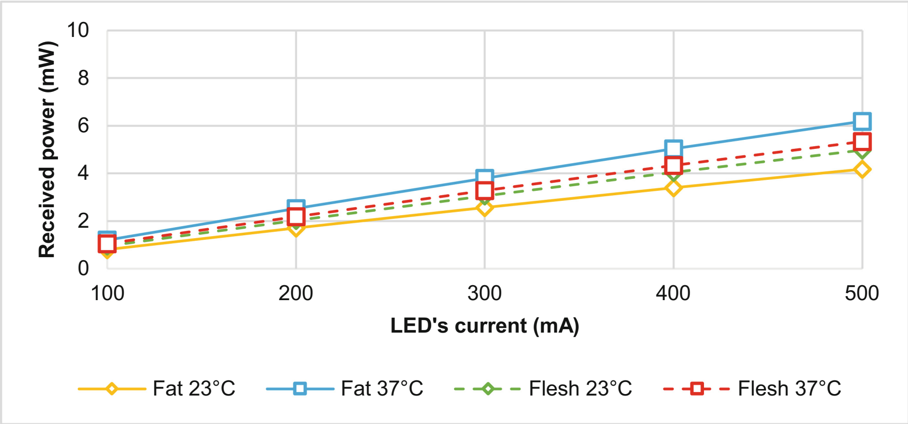


Fig. 2. Experimental setup and details of the employed porcine samples.

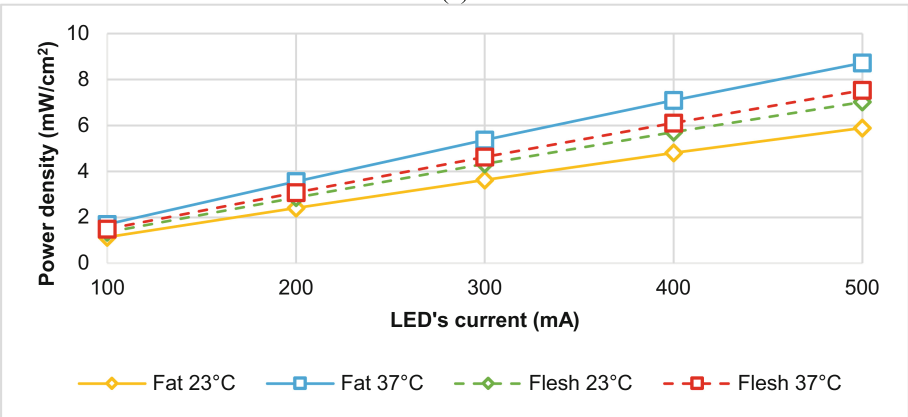
4 Results and Analysis

4.1 Measurement on Fat and Flesh Tissues under Different Temperatures

The results of the measurement of optical power received in mW and power density units for fat and flesh samples under cold (23 °C) and warm (37 °C) conditions are presented in Figs. 3(a) and (b), respectively. It should be noted that the power received increases proportionally with the optical power emitted [35]. For instance, in Fig. 3(a), when the temperature is 37 °C (LED current = 500 mA), the power received in pure fat and flesh samples is 6.19 mW and 5.34 mW, respectively. Similarly, at the same temperature (37 °C), the power received by pure fat and flesh samples is 1.20 mW and 1.05 mW, respectively, when the LED current is changed to 100 mA. The optical power received after passing through the biological tissue is very important parameter as it determines the SNR value.



(a)



(b)

Fig. 3. Measurement results of fat and flesh tissues under different temperatures: (a) received power in mW; (b) power density in mW/cm^2.

The experiment on porcine samples revealed that the optical characteristics of biological tissues are influenced by temperature, leading to changes in transparency and the amount of power received. Our finding suggests that higher levels of transparency on the tissue promote better light propagation through tissue. Figure 3(b) shows that the optical power received by the sample during optical transmission remains lower than the designated safety threshold (below 2 W/cm^2) [29, 30]. For instance, when considering a sample at a temperature of 37 °C with an LED current of 500 mA, the power density received in fat and flesh tissues is 8.72 mW/cm^2 and 7.53 mW/cm^2, respectively. Similarly, at the same temperature (37 °C), fat and flesh receive power densities of 1.70 mW/cm^2 and 1.49 mW/cm^2 with LED current of 100 mA, respectively.

The results indicate that at temperatures close to the human body's temperature (37 °C), the optical penetration of fat tissue is better than that of flesh tissue. Flesh tissue contains the most significant amount of water compared to other constituents, e.g., bone, fat, and skin [36]. Fat tissue demonstrates a better propagation medium when compared to other human tissues, such as flesh tissue, particularly in the case of radio communications, such as ultrawideband (UWB), in terms of signal loss and propagation speed [13, 17].

In the context of meat on cold temperatures (23 °C), it has been observed that optical penetration through flesh tissue is better than that through fat tissue. In contrast, the opposite occurs under warmer conditions (37 °C). One possible reason for the reduced optical penetration in fat tissue under cold conditions is the relatively higher level of light reflection in fat tissue, which can be attributed to its denser nature [3]. Additionally, fat exhibits a higher susceptibility to temperature effects than flesh. Compared to radio waves, particularly UWB technology, optical waves (especially in 810 nm) are less affected by changes in tissue temperature [37], even though the level of optical power received is affected by the temperature of the biological tissue.

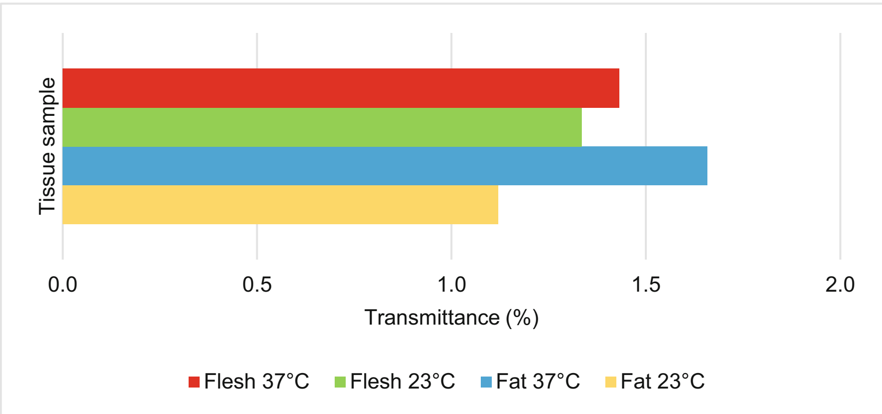
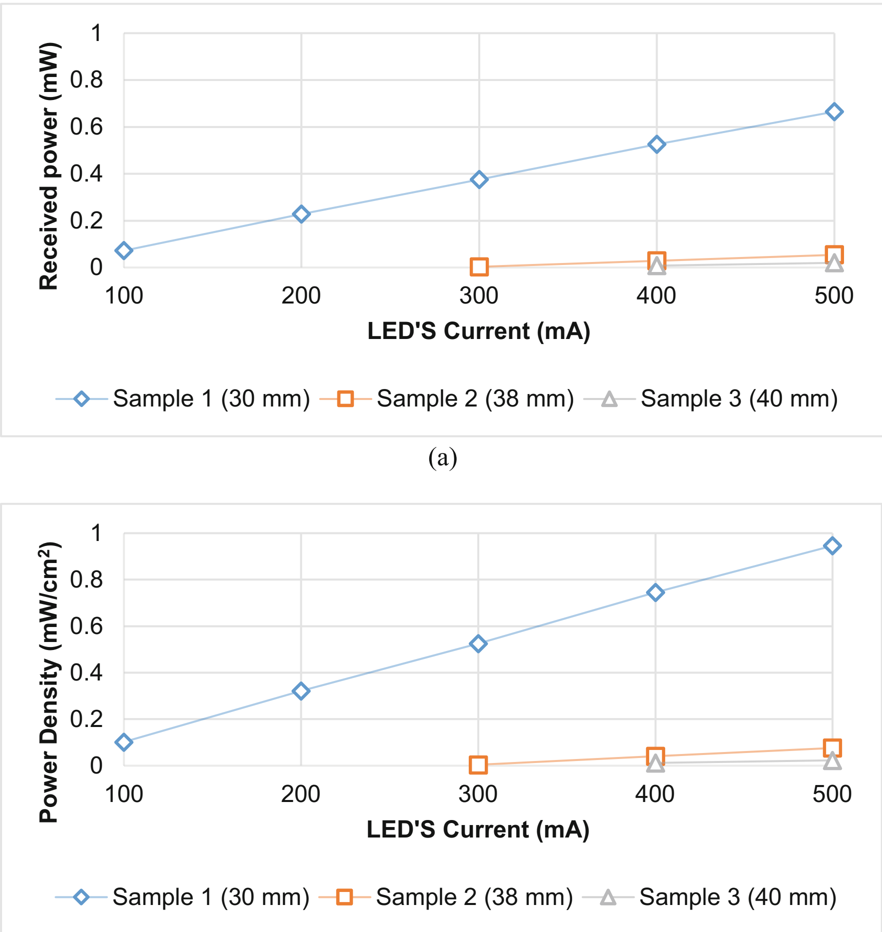


Fig. 4. Transmittance (%) of flesh and fat tissues at 23 °C and 37 °C.

The transmittance rate of porcine samples was obtained to understand better how light penetrates through biological tissues. The transmittance rates were calculated and compared for different LED currents across both tissue samples. Transmittance is a measure of the total amount of light that typically passes through a specific medium and is calculated by dividing the transmitted light's power density by the received light's power density in %, as shown in Fig. 4. The transmittance of fat at temperatures of 23 °C and 37 °C was 1.1% and 1.7% respectively. Similarly, the transmittance of flesh tissue at temperatures of 23 °C and 37 °C was 1.3% and 1.4% respectively.

4.2 Experiments Using Various Thicknesses of Samples

Figure 5(a) and (b) show the measurements results on thicker samples of received power and power density, respectively. Sample #1 denotes a fatty tissue, whereas sample #2 and



(a)

(b)

Fig. 5. Measurement results of experiments using various thicknesses of samples: (a) received power in mW; (b) power density in mW/cm^2.

#sample 3 is considered as musculus tissue. Measurements were conducted at a temperature of 37 °C. The received power measured in sample #1 for LED currents 100 mA, 200 mA, 300 mA, and 500 mA were 0.072 mW, 0.228 mW, 0.376 mW, 0.526 mW, and 0.665 mW, respectively. Correspondingly, the power densities were 0.102 mW/cm^2, 0.321 mW/cm^2, 0.526 mW/cm^2, 0.746 mW/cm^2, and 0.946 mW/cm^2. Samples #2 and #3 exhibited only 5% and 1% power reception relative to sample #1.

The findings suggest that tissue thickness influences the received power and power density level, with samples #2 and #3 not receiving any power when LED power levels were set at 75 and 150 mW. The 810 nm NIR light can penetrate fatty tissue (sample #1) up to 30 mm. However, in the case of thicker tissue, as in samples #2 and #3, 810 nm NIR LED penetration requires a power level of 375 mW. This significant decrease in penetration is attributed to the flesh composition in the tissue, which attenuates the NIR light. Fatty tissue is observed to be a better medium for the propagation of NIR light than musculus tissue.

5 Discussion

OWC is an emerging technology that holds promise as a viable and attractive technology for in-body communication, connecting with modern in-body devices, e.g., pacemakers, cardiac defibrillators, insulin pumps, smart pills, and bio-sensors, instead of relying on RF and acoustic technologies. OWC is a viable communication technology to provide wireless connectivity to in-body and on-body devices, as the optical signal can penetrate biological tissues based on observations of received optical power. According to the literature, OWC is deemed to be a more secure method compared to RF as it uses light waves for data transmission which has limited coverage area and offers faster data transmission speeds than acoustic [3, 26]. This study can support future brain-machine communications as light could be used to securely connect certain parts of the brain to the external world.

We have conducted *ex-vivo* experiments on porcine samples (e.g., pure fat tissue, pure flesh tissue, musculus tissue, and fatty tissue). The porcine serves as a general model for human tissue. The experiments involved using an 810 nm LED as a transmitter, an LED driver to control the LED's current, and an optical power meter to measure the received power after the NIR optical light passes the porcine samples. The optical power is one of the critical factors that can impact the performance of OWC systems within in-body devices; it is closely associated with the SNR. For this reason, measuring received optical factor is very crucial. Pure flesh and fat tissues were compared at different temperatures (23 °C and 37 °C). On the other hand, we also conducted on different thicknesses of porcine sample (fatty and musculus tissues) at fixed temperature close to the human body (37 °C). Using thick sample, it was clear to conclude that the muscular tissue received lower optical power than fatty tissue.

The temperature of porcine sample significantly impacted the optical power received by fat tissue but have minimal effect on flesh tissue. The optical power that went through fat tissue at 23 °C and 37 °C was higher than flesh tissue. The optical power received after the fat tissue experiences a substantial decrease of 60% compared to its power at a temperature of 37 °C, while the reduction in optical power in the flesh tissue is approximately 90%. At a temperature of 37 °C, the optical power after the flesh tissue is 80% of the power after the fat tissue.

This paper provides novel findings over earlier efforts, showing that fat tissue benefits more from heating than in the case of flesh. The study contributes to potential advancements in wireless medical device design and remote healthcare. It is essential to acknowledge that this study was restricted to examining only two varieties of porcine samples (fat and flesh only), different thicknesses were considered, and two temperature levels (23 °C and 37 °C). Future investigations should encompass a wider variety of porcine samples, including different layers with varying compositions of fat, skin, flesh, and bone and different thicknesses. Additionally, exploring a variety of realistic body temperatures (e.g., from 36 °C to 41 °C) holds significant value in the pursuit of further research. However, it is imperative to exercise meticulousness and caution in controlling the temperature of porcine samples using a heater, as excessive heat can cause harm (e.g., exceeding the limits, also sample surface may get dry and then changes in the optical properties). This study focused solely on constant light conditions and did not address achievable rates. Feasibility assessments were based on the received optical power. A subsequent study will integrate the optical front-end to digital signal processing to assess the quality of service (e.g., throughput, bit-error-rate, etc.) on fat tissue propagation under NIR light.

6 Conclusion

The propagation of light through pure fat tissue for optical-based in-body communication has been conducted and we have compared its received power with pure flesh tissue. The experiments also used porcine samples with different thicknesses composed of flesh and fat layers. The impact of sample temperature (cold and warm) was also investigated. The study suggests that heating the meat to 37 °C would be beneficial for a more realistic evaluation of scenarios. The findings of this study provide evidence that the presence of fat layers in porcine sample results in higher received optical power than flesh layers. Furthermore, the study highlights the importance of carefully selecting porcine samples for OWC-based in-body propagation studies, considering the potential impact of meat composition on optical channel characteristics.

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