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Review article

Terahertz Wave Technology for Medical Treatment and Diagnosis

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Abstract

This article provides an overview of the principles, properties, and medical applications of terahertz waves. Terahertz (THz) waves are electromagnetic waves with frequencies ranging from 0.1 to 10 THz, lying between the microwave and infrared regions of the spectrum. They possess unique properties such as the ability to penetrate various materials, a non-ionizing nature, and specific spectral responses to certain biological substances. The working principle of terahertz imaging relies on measuring the absorption, reflection, and scattering of terahertz waves as they pass through biological tissues. Terahertz imaging offers a number of advantages over conventional medical imaging techniques, including higher resolution, better differentiation of soft tissues, and the ability to provide both structural and functional information. Applications discussed in the article include skin cancer detection, dentistry, surgery, and drug monitoring. However, there are challenges and limitations to overcome, such as the need for higher image resolution, miniaturization and improvement of devices, and evaluation of long-term safety. Future opportunities lie in integrating terahertz imaging with artificial intelligence to enhance diagnostic accuracy and efficiency. In conclusion, terahertz waves demonstrate significant potential for various medical applications, offering a safe, non-invasive, and high-resolution imaging modality. While further research and development are necessary to address current limitations, translating this technology into clinical practice could ultimately lead to improved patient care and outcomes.

Keywords: terahertz wave; medical; disease detection

1. Introduction

Terahertz (THz) waves are electromagnetic waves with frequencies ranging from 0.1 to 10 THz, which lie between the microwave and infrared regions of the electromagnetic spectrum (Kurnikov & Bakunov, 2024). In recent years, THz waves have gained significant attention in the scientific and medical communities due to their unique properties, such as their ability to penetrate various materials, their non-ionizing nature, and the specific spectral responses to certain biological substances (Chopard et al., 2023). The potential

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of THz waves for medical applications has been increasingly recognized, particularly in light of the limitations of current medical technologies. For example, X-rays pose risks associated with ionizing radiation, while magnetic resonance imaging (MRI) systems are large and expensive (Constantin, 2020). THz waves are seen as a promising new option for medical imaging, diagnosis, and treatment, owing to their non-destructive nature, high-resolution imaging capabilities, and ability to operate at room temperature (Dressel, 2023). In the realm of medical imaging technologies, THz waves present distinct advantages when compared to conventional methods such as X-rays, MRI, and ultrasound. From a safety perspective, THz waves exhibit low energy characteristics and do not cause molecular ionization or tissue damage, establishing them as a safer alternative to X-ray imaging (Dexheimer, 2020). The short wavelengths of THz waves enable superior image resolution compared to microwave and infrared imaging technologies, facilitating detailed visualization of small anatomical structures (Kamruzzaman et al., 2024). Moreover, THz waves demonstrate effective penetration through non-metallic materials, which significantly reduces external signal interference and enhances overall image quality (Kakikawa et al., 2024). Additionally, the ongoing technological advancement in THz imaging suggests a trajectory toward more compact and cost-effective systems, potentially expanding their accessibility for implementation in general clinical and laboratory settings (Pyatakov et al., 2022).

This article aims to present the concept of applying THz waves in medicine, covering aspects such as imaging, diagnosis, and treatment. It begins by explaining the working principles and properties of THz waves, followed by a discussion of their applications in radiography, skin cancer detection, dentistry, and future trends. The article also analyzes the challenges and opportunities in developing more efficient THz technologies for medical applications to maximize benefits for patient care.

2. Properties of Terahertz

2.1 Working principles and properties of terahertz waves

The working principles and properties of THz waves represent fundamental aspects that distinguish this technology in medical applications. THz waves exhibit unique characteristics that bridge the gap between microwave and infrared radiation in the electromagnetic spectrum, offering advantages not found in other medical imaging and diagnostic technologies. To fully understand their potential in medical applications, it is crucial to examine their frequency characteristics, penetration capabilities, and inherent limitations. This section explores these key properties that make THz waves particularly suitable for medical diagnostics and treatment, while also addressing the challenges that need to be considered for their practical implementation. By understanding these fundamental principles, we can better appreciate the role of THz technology in advancing medical imaging and therapeutic techniques (Khanna, 2021).

2.1.1 Frequency range of THz waves

THz waves occupy the frequency range between 0.1 and 10 THz, corresponding to a wavelength range of 3 mm to 30 μm. This frequency range bridges the gap between the microwave and infrared regions of the electromagnetic spectrum. The unique position of THz waves in the spectrum gives rise to their distinctive properties, which differ from those of neighboring frequency bands (Chopra & Lloyd-Hughes, 2024). The energy of THz photons is relatively low (1-10 meV), making them non-ionizing and safe for biological tissues. However, this low energy also makes THz waves susceptible to absorption by polar molecules such as water, which can limit their penetration depth in certain materials (Oh & Choi, 2022). The electromagnetic spectrum and the position of terahertz waves are illustrated in Figure 1, which shows the dominant LMI mechanisms across the wavelength spectrum and demonstrates how THz waves bridge the gap between the microwave and the infrared regions.

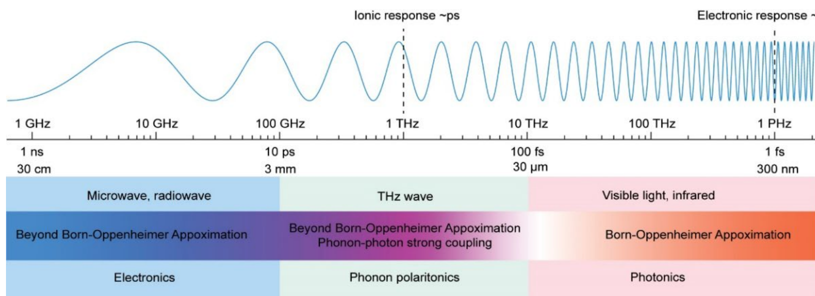

Figure 1. The dominant LMI mechanisms across the wavelength spectrum. Notably, some physical processes, including Raman/Brillouin scattering (although the pump light could be at visible or infrared wavelengths), are beyond Born–Oppenheimer approximations (Lu et al., 2024).

2.1.2 Penetration properties of THz waves through various materials

One of the most prominent features of THz waves is their ability to penetrate a wide range of non-conducting materials, such as clothing, plastics, and biological tissues (Tomimura et al., 2024). This property makes THz waves particularly useful for non-destructive testing and imaging applications. The penetration depth of THz waves depends on the material's absorption coefficient and refractive index, both of which vary with frequency. In general, materials with low water content and low conductivity, such as dry polymers and ceramics, are more transparent to THz waves.

For biological tissues, the penetration depth of THz waves is limited by the high water content, as water strongly absorbs THz radiation. However, THz waves can still penetrate several millimeters into the skin, making them suitable for superficial tissue imaging (Singh & Awasthi, 2024). Studies have shown that THz waves can differentiate between healthy and cancerous skin tissues based on their differences in water content and cellular structure (Jung & Kürner, 2024). Additionally, THz waves can penetrate through clothing and provide high-resolution images of the skin surface, making them potentially useful for security screening and dermatological applications.

2.1.3 Limitations in the use of THz waves

Despite the promising properties of THz waves, there are several limitations to their practical application. One major challenge is the strong absorption of THz radiation by water vapor in the atmosphere, which can significantly attenuate the signal over long distances. This atmospheric attenuation limits the range of THz communication and sensing systems, particularly in humid environments (Singh et al., 2021). To mitigate this issue, researchers have explored the use of low-loss waveguides and high-power THz sources to extend the transmission range (Kulkarni et al., 2022).

Another limitation is the absorption of THz waves by polar molecules, such as water, which are prevalent in biological tissues. The high absorption coefficient of water in the THz range restricts the penetration depth of THz waves in hydrated tissues, typically to a few hundred micrometers. This limitation makes it challenging to use THz waves for deep tissue imaging and sensing. However, researchers have developed advanced signal processing techniques, such as time-gating and deconvolution, to enhance the contrast and resolution of THz images in the presence of water absorption (Kutas et al., 2024).

In summary, while THz waves offer unique properties for various applications, their use is limited by factors such as atmospheric attenuation and absorption by water and other polar molecules. Ongoing research aims to overcome these limitations through the development of advanced THz sources, detectors, and signal processing methods. To better understand the distinctive properties of THz waves compared to other electromagnetic waves used in medical applications, Table 1 provides a comprehensive comparison highlighting the unique characteristics and advantages of THz technology.

From the comparison table of the properties of THz waves with other waves used in medicine, it is evident that THz waves have several unique characteristics that stand out when compared to electromagnetic waves in other frequency ranges.

THz waves have lower frequencies and photon energies than infrared and X-rays, making them non-ionizing and safer for biological tissues. At the same time, THz waves have better penetration capabilities than infrared waves, particularly through non-metallic materials, allowing for more diverse applications.

THz waves provide high-resolution images, capable of distinguishing structures of a few hundred microns, which is better than microwaves and comparable to infrared, but still not as high as the very high resolution of X-rays.

Importantly, THz waves are sensitive to water content and cell structure in biological tissues, enabling better differentiation of soft tissues compared to microwaves and X-rays. This property is particularly useful for detecting tissue abnormalities, such as early-stage tumors and cancers, which may not be easily distinguishable using conventional medical imaging techniques.

Furthermore, THz waves can penetrate the skin up to 1 - 2 mm, covering the epidermis and dermis layers, making them suitable for studying skin structure and abnormalities such as scars, wrinkles, and skin cancer. For such applications, THz waves are much better than infrared waves that demonstrate shallower skin penetration.

With these outstanding properties, THz waves have high potential for various medical applications, ranging from skin cancer detection and dentistry to monitoring drug delivery in the body. However, the practical implementation of THz waves still requires further research and development to improve efficiency and address certain limitations, such as signal attenuation due to absorption by water vapor and water molecules, which is a significant challenge in developing THz technology for biomedical applications.

2.1.4 Wave dispersion and physical properties in THz applications

Wave dispersion is a crucial factor affecting THz wave applications in materials such as water, biological tissues, plastics, and ceramics. This property directly influences wave propagation and impacts imaging, detection, and material analysis capabilities in medical applications. Understanding wave dispersion is essential for optimizing terahertz imaging systems and interpreting results accurately in medical diagnostics.

Table 1. Comparison of the properties of THz waves with other waves used in medicine

Property	Terahertz Waves	Microwaves	Infrared	X-rays
Frequency Range	0.1-10 THz	0.3-300 GHz	0.3-430 THz	30 PHz-30 EHz
Wavelength	30 μm - 3 mm	1 mm - 1 m	700 nm - 1 mm	0.01 nm - 10 nm
Photon Energy	0.4-40 meV	1.2 μeV - 1.2 meV	1.7-1200 meV	100 eV - 100 keV
Ionization	Non-ionizing	Non-ionizing	Non-ionizing	Ionizing
Penetration of Materials	Good penetration through non-metallic materials	Good penetration through some materials	Limited penetration	Good penetration through low-density materials
Image Resolution	High (a few hundred microns)	Moderate (mm)	High (microns)	Very high (microns to nanometers)
Safety for Biological Tissues	Safe	Safe at low power levels	Safe	Unsafe at high doses
Ability to Differentiate Soft Tissues	Good (sensitive to water content and cell structure)	Poor	Good for superficial layers	Poor
Ability to Image Beneath the Skin	Penetrates skin up to 1-2 mm	Penetrates skin deeply	Shallow skin penetration	Penetrates through the skin
Medical Applications	Skin cancer detection, dentistry, drug monitoring	NMR spectroscopy, cancer treatment	Thermal imaging, pulse oximetry	Radiography, computed tomography

Two fundamental physical parameters govern the behavior of THz waves in materials are as follows:

1. The refractive index (n) indicates how THz waves are refracted when passing through different materials. This parameter can vary with the frequency of terahertz waves, resulting in different levels of transparency at various frequencies.

2. The absorption coefficient (α) represents how much terahertz radiation is absorbed per unit distance in materials. This parameter is critical for determining imaging capabilities and penetration depth in biological tissues.

The understanding of these physical properties has profound medical application implications. In tissue imaging and diagnostics, the differential absorption coefficients between normal and cancerous tissues, attributed to variations in water content and cellular structure, serve as the foundation for diagnostic imaging, although water's high absorption coefficient (200-500 cm^{-1}) constrains penetration depth in hydrated tissues. These variations in tissue properties enable the differentiation between healthy and pathological states. The refractive index and absorption coefficient values for common materials used in terahertz applications are summarized in Table 2, which provides essential parameters for understanding material behavior in THz systems.

Table 2. Refractive index and absorption coefficient of common materials in terahertz applications (Dutta et al., 2022; Monnai et al., 2023)

Material	Refractive Index (n)	Frequency Range (THz)	Absorption Coefficient (α) [cm^{-1}]	Properties
Biological Tissues	1.5 - 2.7	0.1 - 1.0	50 - 300	Highly dependent on water content; cancerous tissue can show different absorption to healthy tissue
Water	2.5 - 3.6 (Real part)	0.1 - 3.0	200 - 500	Strongly absorbs THz radiation, leading to very limited penetration depths
Human Skin (Dry)	1.7 - 2.3	0.1 - 1.0	50 - 200	Absorption varies with skin moisture content and frequency
Polymethyl Methacrylate (PMMA)	1.67 - 1.69	0.1 - 1.5	0.3 - 2	Low absorption, commonly used in THz lenses and optics
Silicon	3.42 - 3.46	0.1 - 1.0	0.01 - 0.05	Very low absorption, often used in THz optics and detector systems

In medical device design, materials with low absorption coefficients, such as PMMA (0.3-2 cm^{-1}), prove ideal for terahertz lenses and optical components, while silicon's exceptionally low absorption coefficient (0.01-0.05 cm^{-1}) makes it particularly suitable for detector systems. This understanding of material properties guides the strategic selection of appropriate components for imaging systems.

Regarding clinical applications, skin imaging benefits significantly from the specific absorption properties of dry skin (50-200 cm^{-1}), while the variation in absorption between different biological tissues (50-300 cm^{-1}) facilitates tissue differentiation. Additionally, the sensitivity to water content enables the detection of pathological changes in tissues.

System optimization encompasses the selection of appropriate frequency ranges based on material properties, the design of imaging systems that account for penetration depth limitations, and the development of signal processing techniques to enhance image quality.

These physical properties and their understanding are fundamental to developing more effective terahertz imaging systems, improving diagnostic accuracy in medical applications, optimizing treatment monitoring capabilities, and advancing medical device design. The knowledge of wave dispersion and material properties continues to drive innovation in terahertz medical applications, leading to improved diagnostic and therapeutic capabilities in clinical settings.

2.2 Medical applications of terahertz waves

The medical applications of THz waves have emerged as a significant innovation in modern healthcare technology. These applications leverage terahertz radiation's unique properties to provide solutions for medical imaging, diagnosis, and treatment monitoring. This section explores diverse medical applications of terahertz technology, focusing on key areas such as imaging techniques, skin cancer detection, dental applications, and emerging trends in medical diagnostics (Kubiczek et al., 2024).

2.2.1 Terahertz radiation imaging

Terahertz radiation imaging relies on measuring the absorption, reflection, and scattering of terahertz waves through biological tissues. Wave interaction varies based on tissue composition, including water content, fat, protein, and other components (Denisov et al., 2020; Stringer, 2023).

In terahertz imaging systems, a signal source emits short pulses towards the target tissue, while detectors measure reflected or transmitted signals. Mathematical algorithms then generate cross-sectional images showing absorption and scattering coefficient distribution within tissues, enabling differentiation between normal and abnormal states (Jäckel et al., 2022).

Compared to X-ray imaging, THz waves offer several advantages. Their lower photon energies prevent molecular ionization, making them safer for repeated imaging. Additionally, THz waves excel at differentiating soft tissues with similar densities and can detect molecular-level changes, particularly useful for early-stage disease detection (Shi et al., 2023; Makino et al., 2024).

2.2.2 Skin cancer detection using THz waves

Skin cancer detection utilizes THz wave sensitivity to tissue water content and cellular density. When THz waves are directed onto the skin, cancerous regions show higher absorption due to increased water content and cell density (Kulygin & Litovsky, 2020).

Studies have demonstrated high accuracy in cancer detection using THz waves. Research by Cong et al. (2023) showed 95% sensitivity and 80% specificity for basal cell carcinoma detection compared to histopathology. A study by Walker and Hardwick (2022) achieved 84% sensitivity and 77% specificity in identifying non-melanoma skin cancers.

This non-invasive technique enables real-time imaging and quantitative assessment of lesion depth, size, and shape, facilitating both diagnosis and treatment planning (Bratchenko et al., 2021).

2.2.3 Applications of THz waves in dentistry

Terahertz dental imaging provides high-resolution images of internal tooth structures without harmful radiation. Studies have shown effectiveness in detecting early-stage tooth decay and evaluating dental restorations (Saleeb et al., 2024). Research by Liu et al. (2023) demonstrated clear visualization of tooth structures, distinguishing enamel, dentin, pulp cavity, and root. The technology can reveal details undetectable by conventional radiographs, such as small cavities and spaces within dentin (Shavrov & Shcheglov, 2021). Terahertz imaging in dentistry offers reduced radiation exposure, higher resolution images, and faster examination times compared to traditional radiography (Amirov, 2022).

2.2.4 Trends in other medical applications

Recent developments include applications in minimally invasive surgery, drug monitoring, and disease screening. Studies by Fujita (2020) showed that fiber-optic terahertz endoscopes could clearly display internal organ structures during endoscopic procedures. In drug monitoring, THz waves can track pharmaceutical distribution in tissues through specific molecular interactions. Research by Li et al. (2022) demonstrated measurement of drug concentrations in blood and tissues using low-frequency terahertz spectroscopy. Disease screening applications extend to various internal organs. Lee and Kim (2021) reported success in detecting early-stage colon cancer using terahertz transmission imaging, while Gezimati and Singh (2024) showed promising results in lung cancer detection with 87% sensitivity and 92% specificity.

These applications demonstrate terahertz technology's potential to revolutionize medical diagnostics and treatment methods, though continued development focuses on improving efficiency, stability, and clinical implementation. A simulated medical terahertz imaging laboratory setup demonstrating the practical implementation of THz technology in clinical environments is shown in Figure 2, illustrating the key components required for non-invasive tissue diagnosis.

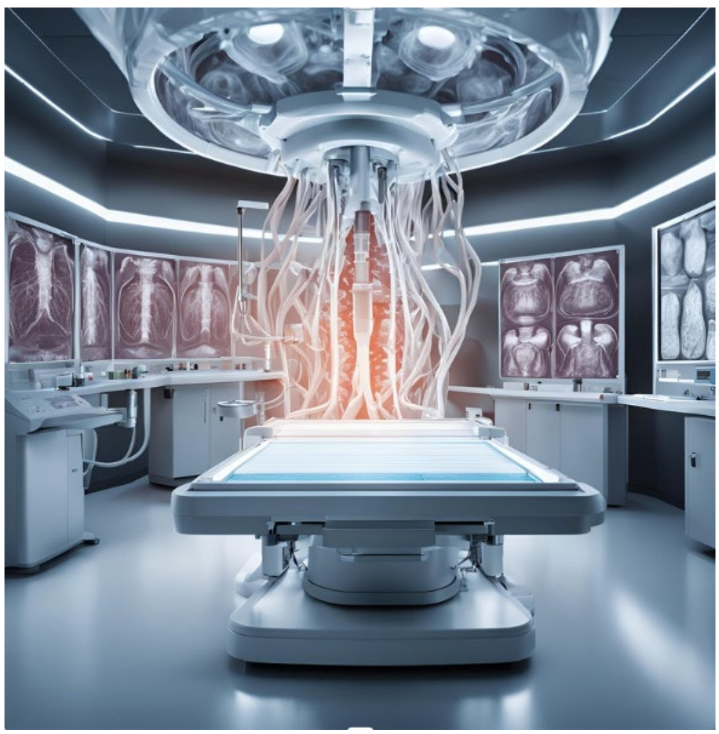

Figure 2. A simulated medical terahertz imaging laboratory features key components: a ceiling-mounted radiation source with cables and waveguides, a central examination table with environmental controls, detection systems measuring wave interactions, and wall-mounted displays showing processed scan images. This setup enables non-invasive tissue diagnosis through automated controls and precise terahertz measurements in a sterile environment.

2.3 Challenges and future opportunities for the use of THz waves in medicine

While terahertz technology demonstrates significant promise in medical applications, it faces several critical challenges that need to be addressed for its widespread clinical implementation. These challenges range from technical limitations in image resolution to practical concerns about device miniaturization and long-term safety considerations. However, these challenges also present opportunities for innovation and advancement in the field. This section examines the current limitations of terahertz technology in medical applications while exploring potential solutions and future developments. By understanding both the obstacles and opportunities, researchers and medical professionals can better focus their efforts on improving this technology's effectiveness and accessibility in healthcare settings (Jung & Kürner, 2024).

2.3.1 Limitations in image resolution and the need for further technological advancements

Although terahertz imaging provides higher resolution images compared to several medical imaging techniques, such as X-rays, MRI, and ultrasound, image resolution remains a significant limitation for certain applications. The spatial resolution of current terahertz images ranges from a few hundred microns to millimeters, which is insufficient for visualizing cellular and tissue details at the microscopic level.

This resolution limitation arises from the physical constraints of THz waves, which have longer wavelengths than visible light, resulting in a limit according to the Abbe diffraction principle. Moreover, image resolution depends on the efficiency of THz wave generators and detectors, which still require development to achieve lower noise and higher sensitivity.

To address the resolution issue, researchers are developing new techniques to enhance the resolution of terahertz images. For example, using metamaterial lenses, which can increase spatial resolution up to 1/6 of the terahertz wavelength (Monnai et al., 2023); employing advanced image processing techniques, such as iterative reconstruction or deep learning to improve image quality and sharpness (Dutta et al., 2022); and developing novel contrast agents that highlight the differences between normal and abnormal tissues in terahertz images (Li et al., 2020).

Despite the challenges in image resolution, advancements in terahertz technology over the past decade, in terms of signal generators, detectors, and processing methods, have greatly improved the resolution and quality of terahertz images. This trend is expected to continue in the future until the resolution of terahertz images becomes high enough to meet the demands for a wide range of medical applications.

2.3.2 The need for miniaturization, portability, and user-friendliness of devices and technology

Currently, most terahertz imaging systems are still large, expensive, and require operation by experts in laboratories, limiting their widespread use in point-of-care testing or large-scale patient screening (Gezimati & Singh, 2023). Therefore, the development of terahertz technology in the future must focus on creating devices that are smaller, portable, affordable, and easy to use by general medical personnel.

Approaches to miniaturizing terahertz devices and making them more user-friendly include the use of high-efficiency semiconductor and integrated circuit technologies such as CMOS and InP technologies to create THz wave generators and detectors; the design of terahertz sensor arrays, which consist of multiple detectors arranged in rows or grids that enable faster image scanning without moving the probe; and the development of portable terahertz imaging systems that integrate the generator, detector, and processing unit into a single lightweight and easy-to-use device (Tzydynzhapov et al., 2020).

In addition to hardware improvements, the development of software and user interfaces is equally important to enable users to collect data, process images, and interpret results conveniently and quickly. Future software systems for terahertz imaging should be automated, user-friendly, and compatible with hospital information systems to facilitate the storage and exchange of patient data (Vogel & Saraceno, 2024).

Developing more compact, flexible, and user-friendly terahertz devices and technologies will increase accessibility and expand the scope of clinical applications, ultimately leading to improved diagnostic and therapeutic quality. However, such development still requires collaboration from multiple stakeholders, including researchers, engineers, physicians, and medical device manufacturers, as well as policy and investment support, to enable terahertz technology to grow and benefit the medical field to its full potential.

2.3.3 Safety of long-term use of terahertz waves on the human body

As terahertz imaging technology has only recently been introduced into medical applications, data on the long-term effects of terahertz waves on human health are still limited. However, studies on the biological effects of THz waves are gaining more attention on the assessment of the safety and potential risks associated with long-term use (Hu et al., 2021).

Generally, THz waves are considered low-energy, non-ionizing electromagnetic waves that do not cause the breakage of atoms or molecules, making them much less harmful to living organisms than X-rays or UV radiation. However, in vitro studies have indicated that exposure to high-intensity THz waves for prolonged periods may induce changes in cells and intracellular components, such as the expression of genes and proteins related to cellular stress and apoptosis (Walker & Hardwick, 2022), and alterations in the electrical conductivity and permeability of cell membranes (Lu et al., 2024).

3. Conclusions

Terahertz (THz) waves are a promising technology for medical applications due to their unique properties, such as the ability to penetrate tissues, their non-destructive nature, and their high-resolution imaging capabilities. Research studies have found that terahertz imaging is beneficial in detecting skin cancer, dental caries, and monitoring drug delivery. However, there are still technical challenges that need to be addressed, such as improving image resolution, developing compact and affordable devices, and investigating the long-term effects on the human body. If these limitations can be overcome, THz waves have the potential to revolutionize the medical field by enhancing the efficiency of disease diagnosis and treatment in the future.

4. Author's Contributions

Ornnicha Kongwut: Conceptualization, literature review, data analysis, and manuscript preparation. Phatsaran Laohhapaiboon: Methodology, manuscript review and editing, supervision, and final approval. Both authors have read and agreed to the published version of the manuscript.

5. Conflicts of Interest

The authors declare that they have no conflicts of interest.

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