DOI: 10.7860/JCDR/2025/80182.22095

Review Article

Radiology Section

Role of Terahertz Radiation in the Detection and Treatment of Cancer: A Narrative Review

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ABSTRACT

Terahertz (THz) waves occupy a distinctive position in the electromagnetic spectrum, between the long-wavelength far-infrared and the high-frequency microwave ranges. THz imaging and spectroscopy have proven useful in identifying tumour margins, assessing biochemical changes, and distinguishing between cancerous and normal tissues in breast, skin, and brain cancers. Experimental studies suggest that THz radiation may also affect cellular structures, offering potential as a treatment method through selective heating and alterations in Deoxyribo Nucleic Acid (DNA) and Ribonucleic Acid (RNA) structures. Advancements in source technology, detector sensitivity, and the application of Artificial Intelligence (AI) are driving progress in this field, while hybrid imaging strategies may further enhance diagnostic accuracy. This review highlights the potential of THz technology as a novel technique for the early diagnosis and treatment of cancer. However, additional research is required to enable its application in medical imaging so that it can compete with conventional techniques such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI), and further develop its potential in cancer therapy.

Keywords: Cancer diagnosis, Cancer treatment, Non-invasive, Terahertz imaging, Terahertz spectroscopy

INTRODUCTION

Terahertz radiation, also known as THz waves, occurs between the high-frequency microwave region and the long-wavelength far-infrared region of the electromagnetic spectrum [1]. Historically, this zone was referred to as the "THz gap" and is typically defined as the frequency range between 0.1 and 10 THz [2]. David Auston made the first significant strides toward bridging the THz gap in 1975 by developing ultrafast femtosecond laser sources at AT&T Bell Laboratories. These sources were used to generate and detect transmitted THz pulses [3]. The first THz image was published in 1995 as a result of advancements in THz Time-Domain Spectroscopy (THz-TDS) and other imaging methods [1].

Over the past two decades, developments in THz instrumentation and imaging have enabled several applications, including high-resolution tissue imaging, cancer diagnostics, biosensing, and biomolecular analysis [4]. THz imaging and spectroscopy are particularly useful for identifying malignant changes, differentiating between healthy and diseased tissues, and analysing macromolecules such as proteins, carbohydrates, and DNA [5]. The growth of advanced technologies, the emergence of new diseases, population health management, and scientific discoveries have further increased the demand for THz technology in healthcare [6].

THz technology is enhancing, and in some cases enabling, the sensing, imaging, and detection of various cancers such as colon cancer [7], skin cancer [8], and breast cancer [9]. Many types of cancer have been found to exhibit a distinct THz resonance fingerprint at 1.65 THz [10]. THz imaging can successfully differentiate between healthy and cancerous tissues due to its sensitivity to tissue morphology and water content. It offers high-contrast, label-free imaging for both in-vivo and ex-vivo diagnostics, making the technique particularly useful for superficial malignancies such as skin, breast, and oral cancers [11,12].

Typical THz absorption and reflection signatures are commonly observed in cancerous tissues because of their high water content and complex molecular structures. This inherent contrast enables the evaluation of surgical margins and precise tumour localisation [12,13]. DNA methylation and demethylation play a significant role in cancer progression and treatment [14]. Resonant THz exposure at specific frequencies has been shown to reduce DNA methylation and inhibit cancer growth, suggesting a novel, non invasive approach to epigenetic cancer therapy, as demonstrated in several studies [4,14,15].

Targeted THz irradiation has also been reported to suppress telomerase activity in cancer cells, leading to cellular ageing, telomere crisis, apoptosis, and decreased tumourigenicity in animal models. These findings demonstrate the potential of THz radiation as a non invasive, non-pharmacological method for cancer treatment [16].

Physics of THz Technology

THz radiation possesses unique characteristics that make it particularly suitable for biomedical research, especially its ability to excite low-frequency molecular vibrational modes, including van der Waals forces, hydrogen bonds, and other non-covalent interactions. THz imaging and spectroscopic systems are essential for identifying, analysing, and visualising biological samples using various detection and signal-processing techniques [17].

THz Imaging System

Over the past two decades, significant advances have been made in THz generation and detection technologies, and several devices are now commercially available [18,19]. Based on the type of THz source used, these systems can be broadly classified into two categories: Continuous Wave (CW) systems and pulsed systems [20].

THz Spectroscopic System

THz spectroscopic devices measure both the phase and amplitude of the sample data. These measurements are then converted into optical parameters such as the absorption coefficient and refractive index. The three primary types of THz spectroscopy commonly employed in biological research are THz Time-Domain Spectroscopy (THz-TDS), photomixing spectroscopy, and Fourier Transform Spectroscopy (FTS) [21].

DISCUSSION

The articles retrieved from the PubMed database served as the basis for this review. A comprehensive search was conducted for articles published between September 2005 and May 2025. The

publications were identified using search terms such as "terahertz imaging" and "cancer imaging and treatment." The selection of articles was limited to studies involving humans, animals, and tissue phantoms. Only those articles whose abstracts and titles were relevant to the topic were included in the final review. According to Global Cancer Observatory (GLOBOCAN) 2022 estimates, there were 19.98 million new cancer cases and 9.74 million cancer deaths worldwide in 2022 [22]. The present review highlighted research developments in the application of THz technology, which is anticipated to become an innovative, near-future approach for diagnosing various types of cancer.

A Continuous Wave Terahertz (CW-THz) system was used in a study to analyse freshly dissected breast and oral tissues. By combining pathology images with THz images, a sophisticated Artificial Intelligence (AI) system was employed to tag each pixel in the THz images. The results demonstrated that low-frequency THz imaging could successfully distinguish between benign and malignant tissues in freshly dissected specimens [23].

In another study, a CW-THz point-by-point scanning method for breast cancer diagnosis was computationally evaluated using a multilayer Three-dimensional (3D) breast model. The results revealed significant variations in the electric field distribution across different tumour sites and sizes, distinguishing healthy from cancerous breast tissue [24].

Recent studies have also made substantial progress in the imaging of brain gliomas and differentiating them from healthy brain tissue, demonstrating the strong potential of THz technology for intraoperative brain tumour localisation. Differences in cell density and the increased water molecule content surrounding tumour regions have been associated with image contrast between normal tissues and gliomas [25].

Freshly extracted normal and glioma brain tissues from mouse models were analysed using THz Attenuated Total Reflection (ATR) imaging in combination with a super-hemispherical Solid Immersion Lens (SIL). The results showed that gliomas in mouse brain tissue could be effectively distinguished from normal brain tissue due to their characteristic THz wave absorption properties [26]. THz spectroscopy and imaging, using both pulsed and continuous-wave methods, have also been applied in the evaluation of skin melanoma, non-melanoma, diabetic conditions, dysplasia, and scarring, based on the optical properties of THz waves [8]. Shur conducted studies assessing skin hydration using either Transmission THz Time-Domain Spectroscopy (TDS) or CW-THz spectroscopy, demonstrating the potential of these techniques to enhance cancer detection and accurately evaluate disease progression in three dimensions [27]. Studies highlighting the diverse applications of THz technology in cancer diagnosis is presented in [Table/Fig-1] [28-43].

In cancer, aberrant DNA methylation leads to abnormal genetic phenotypes that mimic genomic mutations. Although genomic alterations are often irreversible, DNA methylation can be reversed through the process of demethylation [14]. Evidence suggests that the demethylation of malignant DNA plays a major role in initiating cell apoptosis, reducing tumour growth, and restoring gene expression [44,45]. Studies highlighting the application of THz technology in cancer treatment is presented in [Table/Fig-2] [46-49].

Author and year	Country of publication	Study analysis	Oncological case	THz frequency range	THz system	Conclusion
Wallace VP et al., 2006 [28]	United Kingdom	Spectroscopic investigation comparing the THz characteristics (absorption coefficient and refractive index) of dissected normal human skin with Basal cell Carcinoma (BCC)	BCC	0.05-4 THz	THz pulsed spectroscopy	The study showed that the absorption coefficient and refractive indices were higher for BCC.
Sim YC et al., 2013 [29]	South Korea	THz imaging of extracted oral cancer	Oral cancer	0.2-1.2 THz	THz imaging	The results indicated that THz imaging at -20 °C provided higher contrast between the cancerous tissue and the normal mucosa than measurements at room temperature.
Ji YB et al., 2014 [30]	South Korea	Analysis of THz spectroscopy and characteristics of the Gastrointestinal Tract (GIT) in a rat model	Cancers of the GIT	0.5 THz	THz reflection imaging and spectroscopy	The study showed that THz wave analysis could distinguish cancers of GIT in rat model.
Wahaia F et al., 2015 [31]	Portugal	THz spectroscopy analysis of colon cancer tissue encased in paraffin	Colon cancer	0.1-3.5 THz	THz-TDS	The results indicated that all samples exhibited increased absorption, refractive index, and absorption coefficients in the cancerous areas.
Kashanian HA et al., 2015 [32]	Iran	Different intelligent analysis techniques for evaluating THz images from gastric cancer	Gastric cancer	-	THz-TDS	The result showed that different intelligent analyses were helpful in examining all cases of gastric cancer.
Globus T et al., 2016 [33]	USA	Introduction of novel sub-THz resonance spectroscopy with MD computation for potential quantification and optical analysis of molecular biomarkers in ovarian cancer	Ovarian cancer	-	Sub-THz spectroscopy	The study depicted that the Sub-THz spectroscopy method was considered an excellent approach for the diagnosis of ovarian cancer.
Goryachuk et al., 2017 [34]	Russia	Assessment of TDS's viability for differentiating between normal and gastrointestinal cancerous tissues	Gastric cancer	0.1-1.5 THz	THz-TDS	The results showed that gastric cancer tissue could be easily differentiated from normal by using THz-TDS.
Globus T et al., 2019 [35]	USA	Sub-terahertz vibrational spectroscopy of normal control tissue and ovarian cancer for molecular diagnostics	Ovarian cancer	-	Sub-THz spectroscopy	The study found that the Sub-THz spectroscopy method was an efficient method for the diagnosis of ovarian cancer.
El-Shenawee M et al., 2019 [36]	USA	Identification of cancer in extracted breast tumours by THz imaging and spectroscopy	Breast cancer	0.1 to 4 THz	THz imaging and spectroscopy	The results showed a distinct difference between the healthy tissues and cancerous tissues.
Zhang P et al., 2020 [37]	China	Integration of THz imaging and spectroscopy for detection of prostate cancer	Prostate cancer	1.2 THz	THz spectroscopy and imaging	The results showed that the locations of the tumours within the paraffin mass of tissue related to prostate cancer were precisely measured with terahertz spectroscopy and imaging methods combined with the suggested advanced mathematical computation analysis technique.

Hakeem SI and Hassoun ZA 2020 [38]	Iraq	Analysis of skin cancer identification based on Terahertz Images Utilising Gabor Filter and ANN	Skin cancer	-	THz Pulsed Imaging (TPI)	Simulation results were successful with reduced time consumption of cancer diagnosis through the ANN algorithm with 94.117% accuracy.
Zhang T et al., 2020 [39]	Russia	Application of a tissue-mimicking phantom for oral cancer using graphite and polyvinyl chloride plastisol at THz frequencies	Oral cancer	0.1-1 THz	THz-TDS	The Terahertz (THz) optical response of cancerous oral tissue was well represented by a 16.7% water-free graphite phantom, whereas the optical response of normal oral tissue corresponded to a 21.9% graphite phantom.
Cassar Q et al., 2021 [40]	France	Morphological dilatation based on THz refractive index for the delineation of breast cancer	Breast cancer	200 GHz to 2 THz	THz imaging and spectroscopy	The results indicated that morphological dilatation, together with the intrinsic optical properties of tissues, contributed to the maintenance of treatment efficacy in breast-conserving surgery.
Shi W et al., 2021 [41]	China	Transient terahertz spectroscopy for the identification of cervical cancer cells	Cervical cancer	0.1-2.0 THz	THz-TDS	The result showed that the cancers were detected effectively with individual spectroscopic signatures in absorption spectra.
Qi X et al., 2024 [42]	Australia	Investigation of human skin lesions using THz in vivo imaging via a newly developed THz QCL confocal imager	Angioma, seborrheic keratosis, benign naevus, neurofibroma, BCC, mycosis fungoides, actinic keratosis, photodamaged skin, tattoo, and scars	2.85 THz	THz imaging system	THz imaging provided significant added diagnostic power for physicians when used for dermatological evaluation of lesions of the skin.
Hamza MN et al., 2025 [43]	Iraq	Evaluation of ultra-compact metamaterial-based biosensor enabling cervical cancer detection in the THz domain	Cervical cancer	0-1 THz	THz spectrum	The research portrayed that its large-scale numerical tests confirmed its ability to conduct accurate early-phase cervical cancer diagnosis.

[Table/Fig-1]: Definitive highlights of the application of THz technology in cancer diagnosis [28-43].

Author	Country of publication	Study analysis	Oncological case	Frequency range	THz system	Conclusion
Parshina SS et al., 2005 [46]	Russia	Assessment of the THz range at molecular spectrum frequencies of Nitric Oxide (NO) in stenocardia and arterial hypertension cases	Stenocardia and arterial hypertension	THz range between 150.176 and 150.664 GHz, which correspond to the molecular spectral frequencies of NO	NO-terahertz therapy	Application of THz treatment for patients with cardiovascular pathology is perspective, according to the results.
Titova LV et al., 2013 [47]	Canada	Efficiency of THz pulses in the suppression of genes linked to psoriasis and skin cancer	skin cancer and psoriasis	0.2-2.5 THz	Intense THz pulse radiation	It was found that intense THz pulses have a considerable impact on the overall gene expression of human skin.
Cheon H et al., 2019 [48]	South Korea	Assessment of THz demethylation efficiency and research into THz radiation-induced DNA damage	Melanoma	-	THz radiation system	The research concluded that THz demethylation could become an option for cancer treatment.
Geyikoglu MD et al., 2025 [49]	Turkey	Examination of the impact of THz ablation therapy on various types of cancer	Squamous Cell Carcinoma (SCC), breast and colon cancer	1.65 THz	Terahertz wave ablation system	The study revealed that terahertz wave technology holds the promise of curing cancers in different organs.

[Table/Fig-2]: Definitive highlights of the application of THz technology in cancer treatment [46-49].

Further research is required to explore the full potential of THz technology in cancer therapy. Current technological advancements have primarily focused on improving the software and hardware aspects of THz devices. However, the availability of affordable and reliable THz sources and detectors continues to be a major limitation.

CONCLUSION(S)

With its potential to significantly advance healthcare systems, Terahertz (THz) technology is rapidly emerging as a revolutionary tool in cancer diagnosis and treatment. Due to the presence of hydrogen-bond intramolecular vibrational modes, THz radiation exhibits high sensitivity to water molecules, serving as an inherent marker for label-free tissue differentiation. Other noteworthy characteristics of THz radiation include its low photon energy, non invasive, and non-ionising nature. Consequently, THz technology holds great promise for transforming healthcare by enabling early cancer detection, improving therapeutic outcomes, and enhancing overall patient care.

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PLAGIARISM CHECKING METHODS: [Jain H et al.]
- Plagiarism X-checker: Apr 27, 2025
- Manual Googling: Sep 23, 2025
- iThenticate Software: Sep 25, 2025 (8%)

ETYMOLOGY: Author Origin

EMENDATIONS: 6

AUTHOR DECLARATION:
- Financial or Other Competing Interests: None
- Was informed consent obtained from the subjects involved in the study? NA
- For any images presented appropriate consent has been obtained from the subjects. NA

Date of Submission: **Apr 26, 2025**
Date of Peer Review: **Aug 04, 2025**
Date of Acceptance: **Sep 27, 2025**
Date of Publishing: **Dec 01, 2025**