

A Review of Modern Techniques for Skin Cancer Detection Using Imaging, Spectroscopy, and Machine Learning

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Abstract— Skin cancer is one of the most prevalent forms of cancer, requiring early and accurate diagnosis to improve patient outcomes. This study presents a comprehensive review of non-invasive skin cancer detection techniques, including millimeter-wave imaging, microwave reflectometry, bio-impedance analysis, terahertz sensing, and machine learning-based image analysis. These approaches exploit variations in dielectric, structural, and biochemical properties between normal and malignant tissues. The integration of advanced sensing technologies with intelligent classification methods significantly enhances diagnostic accuracy and reliability. However, challenges such as limited penetration depth, data variability, and lack of multimodal integration persist. The study highlights current advancements, identifies key research gaps, and emphasizes the need for hybrid, cost-effective, and real-time diagnostic systems for improved clinical applicability.

Keywords : Skin Cancer Detection, Millimeter-Wave Imaging, Microwave Reflectometry, Bio-Impedance, Terahertz Sensors, Machine Learning, Non-Invasive Diagnosis.

I. INTRODUCTION

Skin cancer is one of the most common and rapidly increasing forms of cancer worldwide, posing a significant challenge to global healthcare systems. Early detection plays a crucial role in improving survival rates and reducing treatment complexity. Traditional diagnostic methods, such as visual inspection and dermo copy, rely heavily on clinical expertise and may lead to misdiagnosis due to the visual similarity between benign and malignant lesions [1]. Therefore, there is a growing need for accurate, reliable, and non-invasive diagnostic techniques that can assist clinicians in early-stage detection.

In recent years, significant advancements have been made in the development of technology-driven approaches for skin cancer diagnosis [2]. Electromagnetic-based techniques, including millimeter-wave and microwave sensing, have gained attention due to their ability to exploit dielectric differences between healthy and cancerous tissues. These methods provide high-resolution imaging and enable the detection of subsurface abnormalities without the need for invasive procedures. Similarly, bio-impedance and terahertz-based sensing techniques offer promising alternatives by analyzing electrical and refractive properties of tissues [3].



Figure 1: Skin Cancer Symptoms and Features

This figure 1 illustrates the common visible symptoms and clinical features of skin cancer, which are essential for early detection. It highlights four key indicators: new or changing moles, irregular borders, red or scaly patches, and sores that do not heal. The first feature shows abnormal growth or changes in size, shape, or color of moles, which may indicate malignancy. The second feature emphasizes uneven or blurred borders, often associated with cancerous lesions. The third feature represents red or inflamed scaly patches that may persist over time. The final feature depicts open sores or wounds that fail to heal, a critical warning sign of advanced skin abnormalities. These visual cues assist in preliminary screening and encourage timely medical consultation for accurate diagnosis.

In addition to sensing technologies, image processing and machine learning techniques have revolutionized skin lesion

analysis [4]. Automated systems can extract features such as color, texture, and shape from thermoscopic images and classify lesions with high accuracy. Furthermore, spectroscopy and molecular-level analysis provide deeper insights into biochemical changes associated with cancer development, enhancing diagnostic precision.

Despite these advancements, challenges such as variability in skin types, limited penetration depth of electromagnetic waves, and lack of standardized datasets remain [5]. This study aims to provide a comprehensive review of existing non-invasive techniques for skin cancer detection, analyze their strengths and limitations, and identify research gaps. The ultimate goal is to highlight the potential of integrating multiple approaches to develop efficient, accurate, and clinically applicable diagnostic systems.

II. LITERATURE REVIEW

2.1 Millimeter-Wave Based Skin Cancer Detection

Millimeter-wave (MMW) technology has emerged as a promising non-invasive approach for early-stage skin cancer detection due to its ability to exploit dielectric contrasts between normal and malignant tissues. A near-field probe operating around 40 GHz demonstrates high lateral sensitivity (0.2 mm) and detection depth (0.55 mm), enabling the identification of small tumor structures while limiting interaction with deeper tissues. The use of substrate integrated waveguide (SIW) technology further enhances fabrication simplicity and cost-effectiveness, making such systems viable for practical clinical deployment.

Additionally, ultra-wideband MMW imaging systems provide high-resolution three-dimensional visualization of skin lesions. A synthetic bandwidth of up to 98 GHz enables precise differentiation between malignant and normal tissues, supported by strong correlation with histopathological findings [4], [15]. These systems leverage frequency-domain imaging algorithms to reconstruct detailed tissue structures, significantly improving diagnostic accuracy.

The effectiveness of MMW techniques is fundamentally linked to the dielectric properties of skin tissues. Comprehensive spectroscopy studies reveal statistically significant differences in permittivity between malignant and normal tissues across a wide frequency range (0.5–50 GHz), validating the feasibility of electromagnetic-based detection approaches [5].

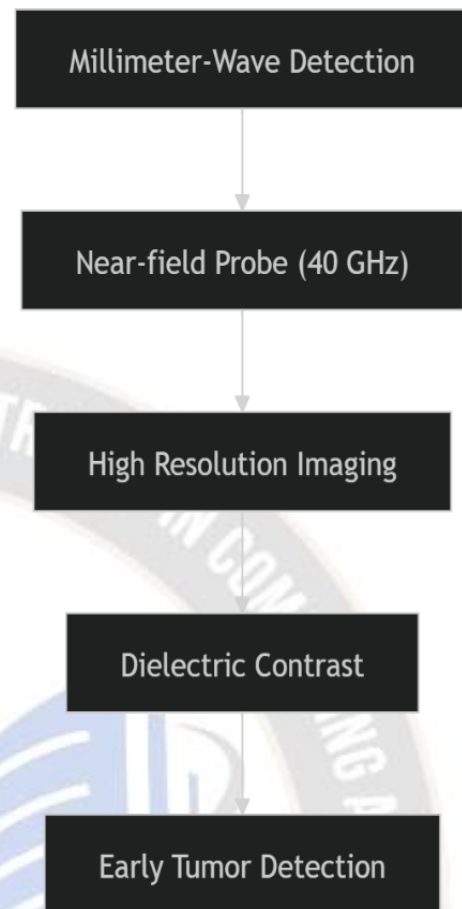


Figure 2: Millimeter-Wave Based Detection

Figure 2 illustrates the workflow of millimeter-wave based skin cancer detection. The process begins with the deployment of a millimeter-wave sensing system, typically operating at high frequencies such as 40 GHz. A near-field probe is used to focus electromagnetic energy on the skin surface, enabling high-resolution imaging. The system exploits dielectric contrasts between normal and malignant tissues, which results in distinguishable signal variations. These variations are processed to achieve early tumor detection with high spatial accuracy and minimal penetration into deeper tissues.

2.2 Skin Phantoms and Experimental Validation

Accurate modeling of human skin is essential for validating detection systems. Skin-equivalent phantoms composed of mixtures such as water, oil, gelatin, and gelling agents have been developed to mimic dielectric properties of both normal and cancerous tissues. These phantoms exhibit strong agreement with real tissue measurements and maintain stability for extended periods, up to seven months [6].

Such models enable controlled experimentation and performance evaluation of imaging systems. Penetration depth analysis shows that millimeter waves can reach approximately 0.6 mm into the skin, effectively covering the epidermis and dermis layers where most skin cancers originate [7]. This validation framework supports the development of reliable diagnostic tools prior to clinical application.

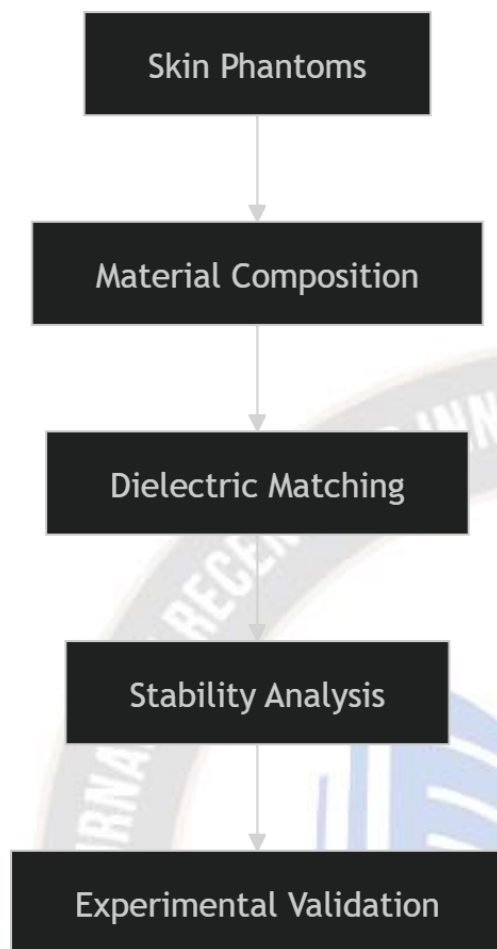


Figure 3: Skin Phantoms

Figure 3 represents the development and utilization of skin phantoms for experimental validation. The process starts with the preparation of phantom materials using specific compositions that mimic biological tissues. These materials are engineered to match the dielectric properties of human skin. Stability analysis is conducted to ensure long-term consistency of the phantom characteristics. Finally, the phantoms are used to validate detection systems under controlled conditions, enabling reliable performance evaluation before clinical application.

2.3 Microwave and Bio-Impedance Techniques

Microwave reflectometry represents another non-invasive method that utilizes variations in reflection properties caused by differences in water content and tissue composition. Experimental studies indicate that malignant lesions exhibit distinguishable reflection characteristics compared to benign and normal skin, enabling effective classification [8].

Similarly, electrical bio-impedance techniques analyze tissue resistance and reactance over multiple frequencies. These methods demonstrate high sensitivity (up to 100%) and good specificity in differentiating malignant melanoma and non-melanoma cancers from benign lesions [9]. The impedance-based approach provides a rapid and cost-effective screening tool, often comparable or superior to conventional visual examination methods.

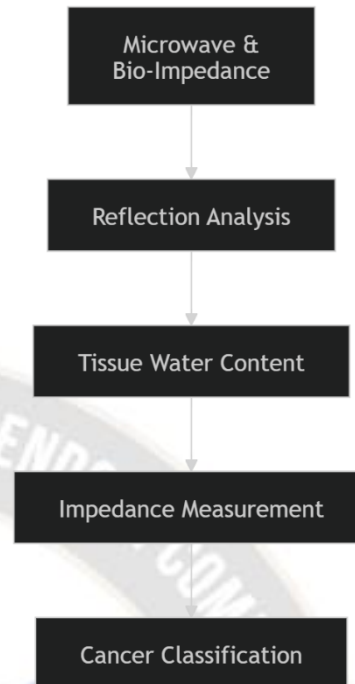


Figure 4: Microwave & Bio-Impedance

Figure 4 demonstrates the methodology of microwave and bio-impedance-based skin cancer detection. The approach involves analyzing reflected microwave signals from the skin, which vary according to tissue composition and water content. In parallel, electrical impedance measurements are performed across multiple frequencies to capture tissue-specific electrical properties. These measurements are then processed to differentiate between normal, benign, and malignant tissues, enabling effective cancer classification.

2.4 Terahertz and Metamaterial-Based Sensors

Terahertz (THz) imaging has gained attention due to its sensitivity to refractive index variations in biological tissues. A water-based metamaterial sensor exhibits enhanced sensitivity and figure of merit, enabling accurate detection of skin cancer through resonance frequency shifts [10]. The strong field localization and bio-compatible design contribute to improved detection performance.

These sensors rely on detecting subtle electromagnetic changes associated with tissue abnormalities, offering a promising direction for high-resolution, label-free diagnostics. Their compact structure and high sensitivity make them suitable for integration into portable diagnostic systems.

2.5 Image Processing and Machine Learning Approaches

Computer vision and machine learning techniques play a critical role in skin lesion analysis. Automated systems using dermoscopy images can segment vascular structures and extract diagnostic features with high accuracy. A framework based on independent component analysis and clustering achieves segmentation sensitivity and specificity of 90% and 86%, respectively, and classification performance of 96.5% AUC for basal cell carcinoma detection [11].

Further advancements include the analysis of dermoscopic patterns such as irregular streaks, which are important

indicators of melanoma. Classification systems utilizing geometric and texture features achieve high accuracy and robust performance across large datasets [12].

Comprehensive reviews of computer vision systems highlight the importance of feature extraction techniques such as segmentation, color analysis, and texture processing, combined with advanced classifiers for improved diagnostic outcomes [16].

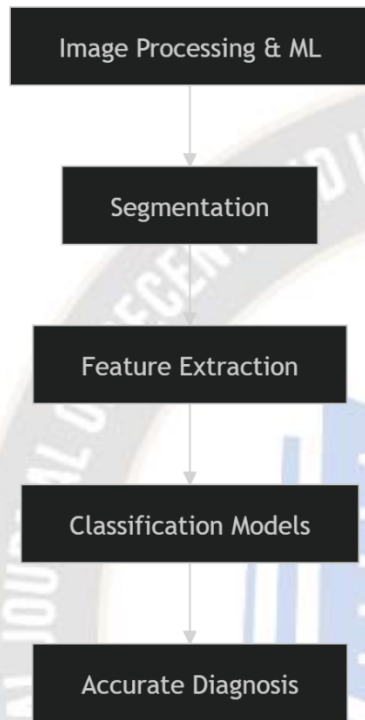


Figure 5: Image Processing & ML

Figure 5 presents the pipeline of image-based skin lesion analysis using machine learning techniques. The process begins with segmentation of thermoscopic images to isolate the region of interest. Relevant features such as texture, color, and vascular patterns are extracted from the segmented regions. These features are then fed into classification models, including machine learning or deep learning algorithms, to accurately distinguish between malignant and benign lesions, improving diagnostic reliability.

2.6 Spectroscopy and Molecular-Level Analysis

Spectroscopy-based techniques provide biochemical insights into skin lesions. Raman spectroscopy combined with neural network classifiers achieves high classification accuracy (up to 94.8%) by analyzing spectral signatures of proteins and lipids [12]. These methods enable objective and automated diagnosis, reducing dependence on subjective visual assessment.

Fluorescence-based diagnostics also contribute to tumor detection by analyzing endogenous and exogenous fluorescence signals. These approaches provide high contrast between malignant and benign tissues, facilitating early detection and differentiation [14].

At the molecular level, gene expression analysis offers a powerful tool for distinguishing multiple skin pathological

states. Integration of transcriptomic datasets enables the identification of key biomarkers, achieving classification performance exceeding 94% in multiclass scenarios [13]. Such approaches support the development of intelligent clinical decision support systems.

2.7 Emerging and Complementary Techniques

Other innovative techniques include optical and biomechanical imaging methods. Digital image-based elasto-tomography demonstrates the ability to detect tumors by analyzing surface motion and tissue stiffness, highlighting the potential of mechanical property-based diagnostics [15].

Electromagnetic antenna sensors have also been explored for melanoma detection, offering insights into wave-tissue interactions and enabling optimization of sensor design for improved reliability [17].

Additionally, studies on radiation-induced carcinogenesis and gene modulation provide a deeper understanding of cancer development mechanisms, supporting preventive and therapeutic strategies [16].

III. RESEARCH GAP

Despite significant advancements in skin cancer detection technologies, several critical research gaps remain that limit their widespread clinical adoption and effectiveness. These gaps span across sensing techniques, experimental validation, data analysis, and system integration.

One of the primary gaps lies in millimeter-wave and terahertz-based detection systems. Although these methods demonstrate high resolution and sensitivity, their practical implementation is still limited by challenges such as restricted penetration depth, variability in skin properties across individuals, and high system complexity. Existing studies focus largely on controlled environments or simulations, with limited real-time clinical validation. Furthermore, most systems operate independently and do not integrate multimodal data, which restricts their robustness in diverse diagnostic scenarios.

Another important limitation is associated with skin phantoms used for experimental validation. While current phantoms successfully replicate dielectric properties of human skin, they fail to fully capture the heterogeneity and dynamic nature of biological tissues, such as blood flow, hydration changes, and structural variations. This creates a gap between laboratory validation and real-world clinical performance. There is a need for more advanced, adaptive phantom models that better represent in vivo conditions.

Microwave and bio-impedance techniques, although cost-effective and non-invasive, suffer from moderate specificity and sensitivity trade-offs. These methods are highly influenced by external factors such as probe pressure, skin hydration, and environmental conditions, which can lead to inconsistent measurements. Moreover, standardized measurement protocols and calibration techniques are lacking, making it difficult to ensure reproducibility across different systems and studies.

In the domain of terahertz and metamaterial-based sensors, while high sensitivity has been achieved, challenges remain in terms of scalability, fabrication complexity, and real-time usability. Most designs are still in experimental stages and

require further optimization for portable and user-friendly clinical devices. Additionally, the interaction of terahertz waves with deeper tissue layers is not yet fully understood, limiting their applicability for comprehensive diagnosis.

Image processing and machine learning approaches have shown promising results; however, they face significant limitations related to dataset quality and generalization. Many models are trained on limited or curated datasets, which may not represent the full diversity of skin types, lesion variations, and imaging conditions. This leads to reduced performance in real-world scenarios. Furthermore, the lack of explainability in advanced models, particularly deep learning systems, poses challenges for clinical trust and adoption.

Spectroscopy and molecular-level analysis techniques provide detailed biochemical insights but are often complex, expensive, and time-consuming. These methods typically require specialized equipment and expertise, limiting their use in routine clinical practice. Additionally, integrating molecular data with imaging or electromagnetic techniques remains an open challenge, which restricts the development of comprehensive diagnostic systems.

Emerging techniques such as elasto-tomography and antenna-based sensing introduce new perspectives but are still in early stages of research. Their clinical validation is limited, and their performance in comparison to established methods is not yet fully established. Moreover, there is a lack of standardized evaluation frameworks to compare different detection modalities effectively.

Overall, a major research gap exists in the integration of multiple detection techniques into a unified, hybrid diagnostic system. Current approaches largely operate in isolation, whereas combining electromagnetic sensing, imaging, machine learning, and molecular analysis could significantly enhance diagnostic accuracy and reliability. Future research should focus on developing cost-effective, portable, and real-time multimodal systems, along with standardized datasets and validation protocols, to bridge the gap between research and clinical implementation.

IV. METHODOLOGY

The proposed methodology for skin cancer detection is designed as a multi-stage, non-invasive framework that integrates electromagnetic sensing, image analysis, and intelligent classification techniques to improve diagnostic accuracy and reliability. The overall process begins with data acquisition, followed by signal or image processing, feature extraction, and finally classification and validation.

In the first stage, data acquisition is performed using appropriate sensing modalities such as millimeter-wave probes, microwave reflectometry, dermoscopic imaging, or spectroscopy-based systems. Depending on the selected technique, the skin region of interest is scanned to capture either electromagnetic response signals or high-resolution images. For electromagnetic methods, parameters such as frequency range, probe positioning, and contact conditions are carefully controlled to ensure consistent measurements. In image-based approaches, dermoscopic images are collected under standardized lighting

and magnification conditions to maintain uniformity across the dataset.

Following data acquisition, preprocessing is applied to improve data quality and remove noise or unwanted variations. In electromagnetic signals, filtering techniques are used to eliminate interference and normalize the measured responses. For image data, preprocessing includes steps such as color normalization, contrast enhancement, and artifact removal (e.g., hair or shadows). These steps are essential to ensure that the subsequent analysis is not affected by external distortions.

The next stage involves segmentation of the region of interest. In image-based methods, segmentation techniques such as thresholding, clustering, or edge detection are used to isolate the lesion area from surrounding healthy skin. For signal-based methods, relevant signal components corresponding to tissue characteristics are extracted. Accurate segmentation is critical as it directly influences the quality of feature extraction and classification.

Feature extraction is then performed to derive meaningful information from the processed data. In electromagnetic approaches, features such as dielectric properties, reflection coefficients, and impedance values are analyzed. In image-based methods, features related to color, texture, shape, and vascular patterns are extracted. Additionally, advanced techniques may incorporate spectral or molecular features, depending on the sensing modality. These features represent the distinguishing characteristics between normal and malignant tissues.

Subsequently, classification is carried out using machine learning or statistical models. Algorithms such as support vector machines, random forests, or neural networks are trained using labeled datasets to differentiate between benign and malignant lesions. The model learns patterns from the extracted features and predicts the class of new, unseen samples. To enhance performance, feature selection and dimensionality reduction techniques may also be applied to remove redundant information.

Finally, the system is validated using performance evaluation metrics such as accuracy, sensitivity, specificity, and area under the curve (AUC). Cross-validation techniques are employed to ensure robustness and generalization of the model. The results are compared with existing methods or clinical findings to assess the effectiveness of the proposed approach.

V. CONCLUSION AND FUTURE WORK

In conclusion, this study highlights the potential of advanced non-invasive techniques for early skin cancer detection by integrating electromagnetic sensing, imaging, and intelligent data analysis methods. The reviewed approaches demonstrate significant improvements in detection accuracy, resolution, and diagnostic capability compared to traditional methods. Techniques such as millimeter-wave imaging, bio-impedance analysis, and machine learning-based classification offer promising solutions for rapid and reliable diagnosis.

However, challenges related to system integration, real-time implementation, and variability in skin characteristics still persist. Future work should focus on developing hybrid multimodal systems that combine multiple sensing techniques

to enhance robustness and accuracy. Additionally, efforts should be directed toward creating large, diverse datasets and improving model interpretability for clinical acceptance. The development of portable, cost-effective devices and real-time diagnostic tools will further bridge the gap between research and practical healthcare applications.

References

1. G. Mansutti, A. T. Mobashsher, K. Bialkowski, B. Mohammed and A. Abbosh, "Millimeter-Wave Substrate Integrated Waveguide Probe for Skin Cancer Detection," in *IEEE Transactions on Biomedical Engineering*, vol. 67, no. 9, pp. 2462-2472, Sept. 2020
2. A. Mirbeik-Sabzevari and N. Tavassolian, "Ultrawideband, Stable Normal and Cancer Skin Tissue Phantoms for Millimeter-Wave Skin Cancer Imaging," in *IEEE Transactions on Biomedical Engineering*, vol. 66, no. 1, pp. 176-186, Jan. 2019
3. P. Kharazmi, M. I. AlJasser, H. Lui, Z. J. Wang and T. K. Lee, "Automated Detection and Segmentation of Vascular Structures of Skin Lesions Seen in Dermoscopy, With an Application to Basal Cell Carcinoma Classification," in *IEEE Journal of Biomedical and Health Informatics*, vol. 21, no. 6, pp. 1675-1684, Nov. 2017
4. A. Mirbeik-Sabzevari, E. Oppelaar, R. Ashinoff and N. Tavassolian, "High-Contrast, Low-Cost, 3-D Visualization of Skin Cancer Using Ultra-High-Resolution Millimeter-Wave Imaging," in *IEEE Transactions on Medical Imaging*, vol. 38, no. 9, pp. 2188-2197, Sept. 2019
5. A. Mirbeik-Sabzevari, R. Ashinoff and N. Tavassolian, "Ultra-Wideband Millimeter-Wave Dielectric Characteristics of Freshly Excised Normal and Malignant Human Skin Tissues," in *IEEE Transactions on Biomedical Engineering*, vol. 65, no. 6, pp. 1320-1329, June 2018,
6. P. Aberg, I. Nicander, J. Hansson, P. Geladi, U. Holmgren and S. Ollmar, "Skin cancer identification using multifrequency electrical impedance-a potential screening tool," in *IEEE Transactions on Biomedical Engineering*, vol. 51, no. 12, pp. 2097-2102, Dec. 2004
7. A. Keshavarz and Z. Vafapour, "Water-Based Terahertz Metamaterial for Skin Cancer Detection Application," in *IEEE Sensors Journal*, vol. 19, no. 4, pp. 1519-1524, 15 Feb. 15, 2019,
8. P. Mehta, K. Chand, D. Narayanswamy, D. G. Beetner, R. Zoughi and W. V. Stoecker, "Microwave reflectometry as a novel diagnostic tool for detection of skin cancers," in *IEEE Transactions on Instrumentation and Measurement*, vol. 55, no. 4, pp. 1309-1316, Aug. 2006
9. M. Sadeghi, T. K. Lee, D. McLean, H. Lui and M. S. Atkins, "Detection and Analysis of Irregular Streaks in Dermoscopic Images of Skin Lesions," in *IEEE Transactions on Medical Imaging*, vol. 32, no. 5, pp. 849-861, May 2013
10. T. Botterill, T. Lotz, A. Kashif and J. G. Chase, "Reconstructing 3-D Skin Surface Motion for the DIET Breast Cancer Screening System," in *IEEE Transactions on Medical Imaging*, vol. 33, no. 5, pp. 1109-1118, May 2014
11. F. J. Burns, S. Chen, G. Xu, F. Wu and M. Tang, "The Action of a Dietary Retinoid on Gene Expression and Cancer Induction in Electron-irradiated Rat Skin," in *Journal of Radiation Research*, vol. 43, no. Suppl, pp. S229-S232, Dec. 2002
12. S. Sigurdsson, P. A. Philipsen, L. K. Hansen, J. Larsen, M. Gniadecka and H. C. Wulf, "Detection of skin cancer by classification of Raman spectra," in *IEEE Transactions on Biomedical Engineering*, vol. 51, no. 10, pp. 1784-1793, Oct. 2004
13. J. M. Gálvez *et al.*, "Towards Improving Skin Cancer Diagnosis by Integrating Microarray and RNA-Seq Datasets," in *IEEE Journal of Biomedical and Health Informatics*, vol. 24, no. 7, pp. 2119-2130, July 2020
14. E. G. Borisova, L. P. Angelova and E. P. Pavlova, "Endogenous and Exogenous Fluorescence Skin Cancer Diagnostics for Clinical Applications," in *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 20, no. 2, pp. 211-222, March-April 2014
15. A. Mirbeik-Sabzevari, S. Li, E. Garay, H. -T. Nguyen, H. Wang and N. Tavassolian, "Synthetic Ultra-High-Resolution Millimeter-Wave Imaging for Skin Cancer Detection," in *IEEE Transactions on Biomedical Engineering*, vol. 66, no. 1, pp. 61-71, Jan. 2019
16. I. Maglogiannis and C. N. Doukas, "Overview of Advanced Computer Vision Systems for Skin Lesions Characterization," in *IEEE Transactions on Information Technology in Biomedicine*, vol. 13, no. 5, pp. 721-733, Sept. 2009
17. D. Caratelli, A. Massaro, R. Cingolani and A. G. Yarovoy, "Accurate Time-Domain Modeling of Reconfigurable Antenna Sensors for Non-Invasive Melanoma Skin Cancer Detection," in *IEEE Sensors Journal*, vol. 12, no. 3, pp. 635-643, March 2012